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April 2002 Working Group Meeting on Heavy Vehicle Aerodynamic Drags: Presentations and Summary of Comments and Conclusions

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U.S. Department of Energy

Lawrence Livermore National Laboratory

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April 2002
Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentations and Summary of Comments and Conclusions

Jointly written by
Lawrence Livermore National Laboratory
Sandia National Laboratories
University of Southern California
California Institute of Technology
NASA Ames Research Center
Georgia Tech Research Institute
Argonne National Laboratory

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory on April 3 and 4, 2002. The purpose of the meeting was to present and discuss technical details on the experimental and computational work in progress and future project plans. Representatives from the Department of Energy (DOE) Office of Transportation Technology Office of Heavy Vehicle Technology (OHVT), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), NASA Ames Research Center, University of Southern California (USC), and California Institute of Technology (Caltech), Georgia Tech Research Institute (GTRI), and Argonne National Laboratory (ANL), Volvo Trucks, and Freightliner Trucks presented and participated in discussions. This report contains the technical presentations (viewgraphs) delivered at the Meeting, briefly summarizes the comments and conclusions, and outlines the future action items.

Introduction, Overview of the Project, and Summary

The meeting began with an introduction by LLNL s Deputy Associate Director of the Energy and Environmental Directorate, Ray Smith, where he emphasized that the Nations dependence on oil is a national security issue and that minimizing vehicle aerodynamic drag will significantly reduce the dependence on foreign oil resources. Rose McCallen of LLNL followed with an overview of the DOE project goals, deliverables, and FY02 activities. The viewgraphs for the project introduction and LLNL overview are attached at the end of this report.

Sid Diamond of DOE OHVT announced to the participants that OTT was being reorganized and that certain key aspects of OTT such as OHVT have been incorporated into the FreedomCAR and Vehicle Technologies Programs. This represents a reduction from 6 to 2 Deputy Assistant Secretaries and a reduction of 31 to 11 offices. He assured all that the FY03 budget was secure and that information about FY04 would be forthcoming. Sid also emphasized the importance of reducing energy use to reduce our nations dependence on oil and the relation to national security. In addition to aerodynamic drag reduction, Sid mentioned the importance of developing means for high-density energy storage and efficient energy conversion. Jules Routbort of DOE OHVT/ANL also discussed the push for more electronics in vehicles because of lighter weight and durability.

In summary, the technical presentations at the meeting included a review of experimental results and plans by USC and NASA Ames, the computational results from LLNL and SNL for the integrated tractor-trailer benchmark geometry called the Ground Transportation System (GTS) Model, and turbulence model development and benchmark simulation for rounded cube shapes representative of a tractor and trailer being investigated by Caltech. NASA Ames also presented information on the new geometry called the Generic Conventional Model (GCM) that was evaluated last year in the 7-ft. x 10-ft. wind tunnel at NASA and plans for testing in the 12-ft pressure wind tunnel this year. USC is also investigating an accoustic drag reduction device that has been named Mozart and GTRI continues their investigation of a blowing device. ANL presented their plans for a DOE supported Cooperative Research and Development Agreement (CRADA) with Paccar Truck Company utilizing commercial software tools to simulate the flow and drag for an actual Tractor. Much of the discussion involved wind tunnel testing plans, analysis of existing experimental data, investigations of drag reduction devices, simulation results, and needed modeling improvements. Further details are provided in the attached viewgraphs.

Project Goals, Deliverables, and Future Activities

Based on discussions at the Meeting, the project goals remain unchanged:

- Perform heavy vehicle computations to provide guidance to industry
- Using experimental data, validate computations
- Provide industry with design guidance and insight into flow phenomena from experimental and computations
- Investigate aero devices (e.g., boattail plates, side extenders, blowing and Mozart device)

The following additional activities were identified:

1) Invite industries overseas R&D contacts to UEF Conference.
2) All DOE Team members submit abstracts to UEF Conference.
3) Obtain more funding for UEF Conference.

4) Submit papers for SAE March 2003 conference. The paper submission deadline is June 1st and final manuscripts are due December 10. (Participation by the Team may be limited because of demand by UEF Conference.)
5) Respond to DOE/OHVT request for proposals (RFP) in collaboration with Freightliner on topic of full-scale experiments, instrumentation techniques, and computations.
6) Discuss with International a possible RFP on splash and spray. (USC has a small moving-ground-plane wind tunnel coming online in about six months and LLNL is interested in spray modeling.)
7) LLNL will consult Caltech on guidance in improving boundary layer (near wall) treatment with LES.
8) Demonstrate use of smaller machines (e.g., Linux/PC clusters).
9) RANS for FY02
   a) SNL: Simulate GTS at 0 degree yaw using 1) Wilcox k-omega, 2) Spallart-Almaras, and maybe 3) k-epsilon turbulence models for a minimum of 2 grids and if possible, 3 grids for each.
   b) LLNL:
      i) Document GTS and Texas A&M simulations using Spallart-Almaras model with 2 grids at 0 degree yaw and 1 grid at 10 degree yaw
      ii) Attempt GCM simulation using Overflow code with RANS k-omega tubulence model at 0 degree yaw with 1 grid

Technical Discussion Highlights

Analysis of NASA s Experimental Data on GTS and GCM Geometries in the NASA 7-ft x 10-ft Wind Tunnel

Jim Ross of NASA Ames provided some interesting findings through their analysis of the data from tests done on the GTS geometry in the 7-ft x 10-ft wind tunnel at NASA Ames. The instantaneous PIV measurements of the wake flow were evaluated by conditioned sampling . Condition sampling is performed by calculating the instantaneous vorticity from the measured instantaneous velocity, then searching the results for the maximum vorticity location. This location should point to the center of an eddy, thus, capturing the vortex shedding from the rear of the trailer.

Analysis of the results indicate a Strouhal number $St = FL/V = 0.128$ where F is the vortex shedding frequency (approximately 1180 Hz), L is the boundary layer thickness upstream, and V is the freestream velocity (approximately 92 m/s). It is also observed that there is not a strong correlation of the vortex shedding from the top and bottom of the trailer and that boattail plates not only narrow the wake, but they stabilize it as indicated by a reduction in wake flapping with the bottail plates.

Analysis of PIV data in the gap of the GCM geometry indicates a hysteresis in the flow. It was found that the established recirculating gap flow persists for variations in yaw until the flow finally blows through at the highest yaw angles. What is important to note is that the vehicle exhibits the lowest drag at the yaw angle where blow through occurs. If this blow through characteristic can be artificially reproduced, it can provide a significant reduction in drag. It was also noted that side extenders significantly reduce drag and do not exhibit flow hysteresis.

Determining Weaknesses and Strengths of Reynolds-Averaged Navier-Stokes (RANS) Turbulence Modeling

Walt Rutledge of SNL discussed the wall resolution requirements for RANS turbulence modeling. Calculations indicate that RANS simulations do not show convergence to a steady solution if the y+ of the grid is too large ($y+ = u_\tau y/\nu$, where $u_\tau = (\tau_w/\rho)^{1/2}$ the friction velocity) and is a measure of how well the flow boundary layer is being captured). With the Wilcox k-omega model, a y+ of 2 or less is required for solution convergence, whereas the standard k-epsilon model requires a y+ of 10 or less for solution convergence.

Advantages of Overset Grid Technology

Dora Yen-Nakafuji of LLNL demonstrated the benefits of using overset grid technology. Overset grids provide the flexibility of defining a simple regular grid for the freestream flow in the wind tunnel while allowing the user to separately specify and overlay a fine grid around the vehicle geometry. Thus, the addition of even more detailed components, like side mirrors, is trivial. This technology is currently being utilized by the industry in evaluating production aircraft.

In addition to their work with finite element methods and large-eddy simulation, the LLNL Team has recently been applying the NASA Overflow code, which uses overset grids with a steady Spallart-Allmaras (RANS) turbulence model. Preliminary simulations of the wind tunnel and GTS geometry show impressive performance (i.e., efficient use of computational resources and run time speed). The simulation runs well on a single processor PC and setup time is minimal. The LLNL Team plans to further investigate this technology for application to heavy vehicles and work with NASA to possibly incorporate an advance turbulence modeling technique for large-eddy simulation with the overset technology.

Truck Aero Team Meeting Attendees

LLNL, Livermore, CA

April 3 & 4, 2002

Attendee	Organization	e-mail address and phone
Diego Arcas	USC	arcasrod@usc.edu, 323-936-7298
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Tim Dunn	LLNL	dunn13@llnl.gov, 925-422-5258
Bob Englar	GTRI	bob.englar@grti.gatech.edu, 770-528-3222
Mustapha Hammache	USC	hammache@usc.edu, 213-740-5377
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Kambiz Salari	LLNL	salari1@llnl.gov, 925-424-4635
Dale Satran	NASA ARC	dsatran@mail.arc.nasa.gov, 650-604-5879
Ray Smith	LLNL	smith40@llnl.gov, 925-422-7802
Dave Weber	ANL	dpweber@anl.gov, 630-252-8175
Skip Yeakel	Volvo	**skip.yeakel@volvo.com**

AGENDA

Heavy Vehicle Aerodynamic Drag: Working Group Meeting
Lawrence Livermore National Laboratory
Livermore, CA

April 3 & 4, 2002
Building 123, Conf. Room A

Purpose of Meeting

Presentation & discussion of industry s perspective and activities
Presentation & discussion of technical details of work in progress & future plans

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Wednesday, April 3

7:30	8:00	Badging at West Badge Office (Building 71) and travel to conference room	

Introduction

7:45	8:15	Continental breakfast served in meeting room	
8:15	8:30	Welcome & introduction	Ray Smith, Rose McCallen
8:30	9:00	DOE/OHVT update & budget	Sid Diamond, Jules Routbort

Work Plans and Progress: Experimental Effort and Devices

9:00	9:15	Overview and objectives	Rose McCallen
9:15	10:15	NASA data reduction, analysis, documentation, & test plans	JT Heineck, Jim Ross, Dale Satran
10:15	10:30	Break	
10:30	11:30	USC experimental & numerical results for trailer-base add-ons: a progress report	Diego Arcas, Fred Browand, Mustapha Hammache, Tsun-Ya Hsu
11:30	12:30	GTRI test results & plans for aero device	Bob Englar
12:30	1:15	Lunch at LLNL served in meeting room	

Work Plans and Progress: Computational Effort

1:15	1:30	Overview and objectives	Rose McCallen
1:30	2:30	SNL RANS computations, analysis & DES development	Walt Rutledge, Mary McWherter-Payne, Chris Roy
2:30	3:30	LLNL LES/DES incompressible computations/analysis & development	Kambiz Salari, Jason Ortega, Dora Yen-Nakafuji, Tim Dunn
3:30	3:45	Break	
3:45	4:45	Caltech vortex method development & computations	Philippe Chatelain, Tony Leonard, Mike Rubel
4:45	5:45	Results with a commercial tool	Dave Weber, Dave Pointer

5:45	6:00	Discussion and Wrap-up	
7:00		Dinner at Kawa Sushi in Livermore	

Thursday, April 4

7:30	8:00	Continental Breakfast	

Summary and Discussion

8:00	8:30	Summary of issues from previous day, discussion	Rose McCallen

Industry Perspective & Activities

8:30	9:00	Volvo	Skip Yeakel
9:00	10:00	Overflow from previous day	
10:00	10:15	Break	
10:15	12:00	Discussion & wrap up	

'Working Group Meeting'
Consortium for Aerodynamic Drag of Heavy Vehicles
Department of Energy, Office of Heavy Vehicle Technology
April 3-4, 2002

Rose McCallen, Kambiz Salari, Tim Dunn, Jason Ortega, Dora Yen Nakafuji

Walter Rutledge, Mary McWherter-Payne, Chris Roy, David Kuntz

James Ross, Dale Satran, J.T. Heineck, Bruce Storms, David Driver, James Bell, Steve Walker, Gregory Zilliac

Mustapha Hammache, Fred Browand, *Tsun*-Ya Hsu, Diego Arcas

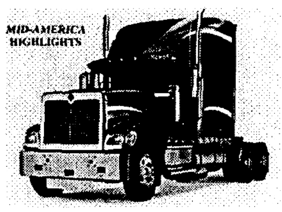
Anthony Leonard, Mike Rubel, Philippe Chatelain

Robert Englar

David Weber, David Pointer, Tanju Sofu

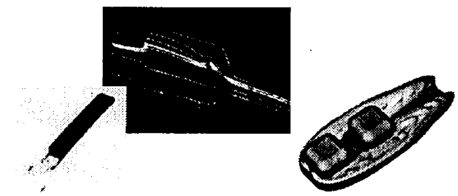
*Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

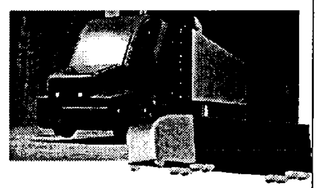
The consortium was formed to provide advanced technology to industry.



Needed for *significant impact on drag*
- Integrated tractor-trailer
- Drag reduction devices
- Aerodynamic
  - Front-end shape   trailer-base
  - components   underbody
- Improved thermal management (underhood flow)

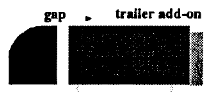
Needed Technologies
- Coupling experiments and computations for design guidance
  - Advanced computational methods and tools
  - Experimental validation
  - State-of-the-art experimental techniques
- Design and testing



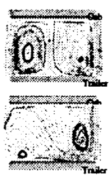


LLNL, SNL, ANL, Caltech
High quality numerical computations
Guidance on computational tools

NASA, USC
Data base of high quality
wind tunnel experiments

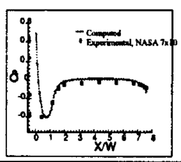


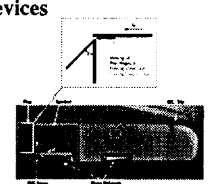
USC, NASA, LLNL, SNL
Comparisons and analyses
Insight into flow phenomena



USC, GTRI
Concepts and designs of
aero devices

TEAM, Industry
Information exchange





The FY02 near-term deliverables include experiments, computations, design, and information exchange with industry.

Guidance for the design of heavy vehicles

- Analysis of existing experimental data
- Comparison to RANS, LES, and DES computations
- New Experiments: Re sensitivity, aero devices, gap and base drag, etc.

Device to reduce base drag

- Experimental validation of an acoustic device
- Full-scale road experiments on blowing device

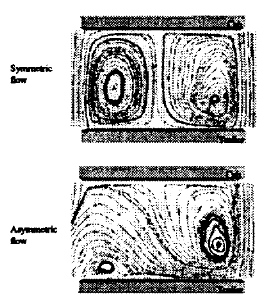
Model development

Information exchange with industry

- Working group meetings, conference papers, site visits

Engineering Foundation Conference

- "Aerodynamics of Trucks, Busses, and Railcars"



GTS Wake Analysis
Flow Structures and Effect of Boat-Tail Plates

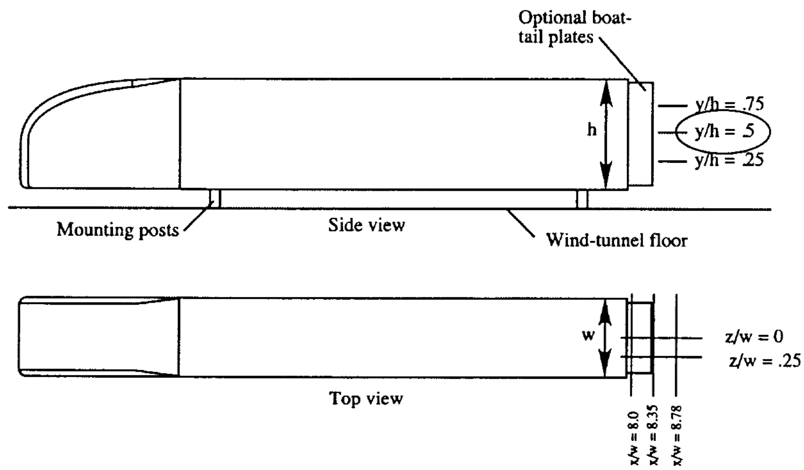
Ames Research Center
Experimental Physics Branch

Outline

- Analysis method to facilitate comparison between instantaneous PIV and LES results
- Look at how boat-tail plates modify wake
- Corrections to PIV data to fix Δt uncertainty

Ames Research Center
Experimental Physics Branch

GTS Wake Measurement Planes



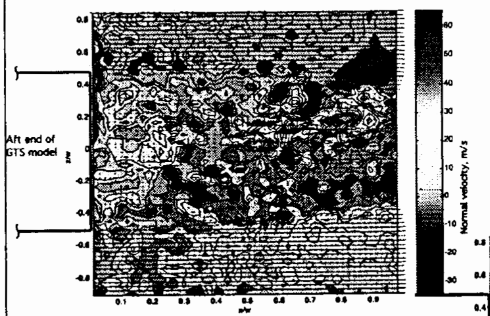
Experimental Physics Branch

Conditional Sampling of PIV Data

- **Accepted a data set based on level of vorticity in a prescribed area in wake shear layer**
- **Can be sampled for both left and right shedding events**
- **Proper selection of level and sample area gave 6-12 hits per 100 data sets**

Experimental Physics Branch

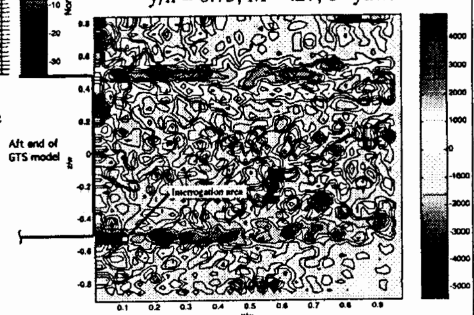
Instantaneous PIV Data



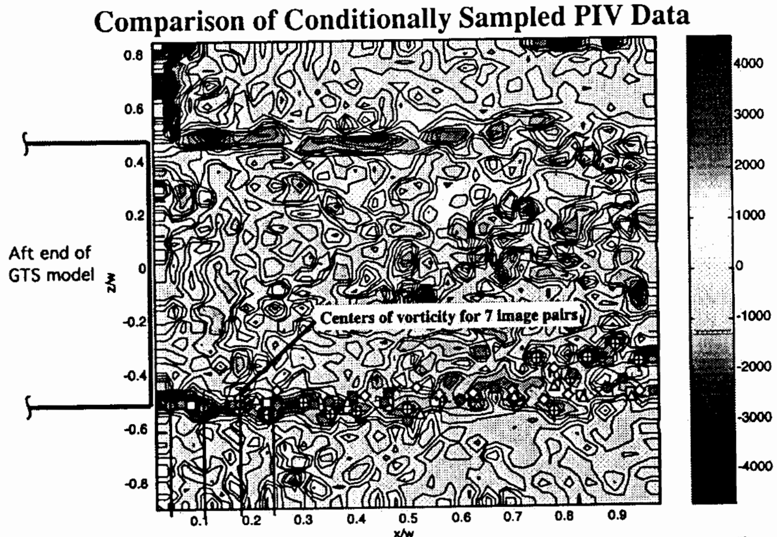
Instantaneous velocity field in wake
y/h = 0.75, M = .27, 0° yaw.

Data is on 56x66 grid (3696 points)

Instantaneous normal vorticity in wake
y/h = 0.75, M = .27, 0° yaw.

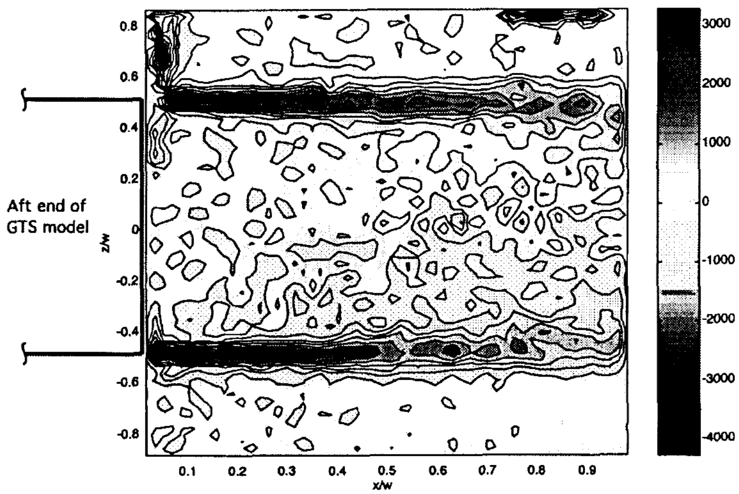


Comparison of Conditionally Sampled PIV Data



Experimental Physics Branch

"Phase" Averaged Vorticity



Strouhal Number of Shear Layer Flow Structure

$$St = \frac{f\,L}{V}$$

f = frequency, L = characteristic length, V = reference velocity

For a turbulent shear layer, $St = 0.128$ where L = Maximum slope thickness, and $V = V_\infty$ (Browand & Trout)

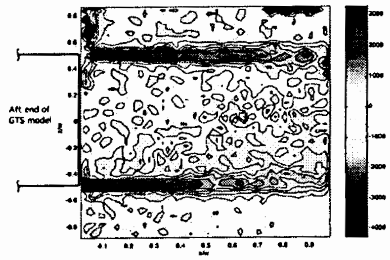
With V = 92 m/s, the shedding should occur at a frequency of ~ 1180 Hz.

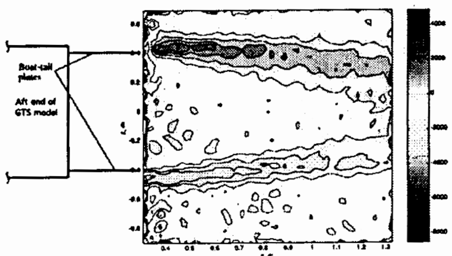
The spacing between eddies is 0.021m giving a convection velocity of 25 m/s

For this kind of shear layer, the convection velocity should be 50-60% of free stream so ...?

Effect of Boat-Tail Plates on Wake

- Boat-tail plates cause wake to close more quickly
- Also stabilize the wake, reducing the lateral oscillations





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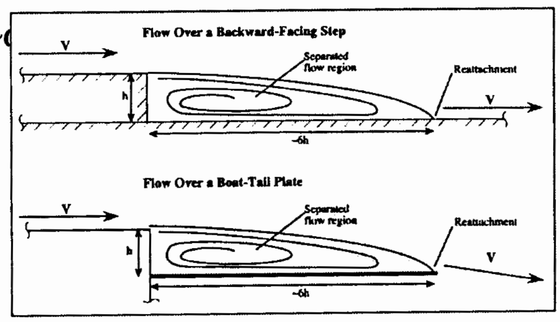
Flow Mechanism Responsible for Boat-Tail Plate Effect on the wake

- Acts like backward-facing step
- Flow reattaches at ~(step heights
- If plate ends near reattachment, wake closes due to fluid momentum toward model centerline
- Full-scale data indicates best drag reduction for plates 5-6 step heights in length



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PIV Data Correction

- Errors in reported velocity measurements identified
  - Seems to be a problem with Δt so it is an incorrect scaling, not an offset
  - Free stream ~10% off for horizontal and streamwise planes - up to 25% for cross-stream planes
- Data has been re-reduced to report 3 velocity components normalized by "free stream"
  - Location of free-stream identified for each measurement plane
  - Comparisons with CFD still possible if similarly normalized
  - Will distribute normalized data on CD

Experimental Physics Branch

Generic Conventional Model (GCM) Truck Test in 7x10 and12-Ft.

Dale Satran
dsatran@mail.arc.nasa.gov
650-604-5879

Heavy Vehicle Aerodynamic Drag

Experimental Physics Branch

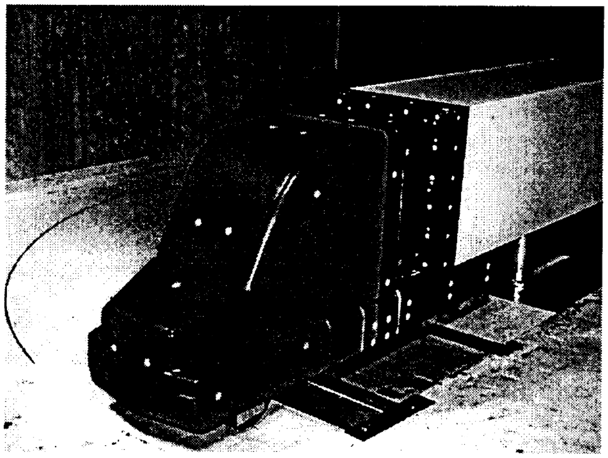
Deliverables

- Digitized model geometry
- CFD validation data
- Reynolds Number effects
- Drag reduction
- PIV data
- Final reports

Actions

- Digitize model
- Analyze 7 x 10 results
- Modify model based on 7 x 10 results
- Modify model for mounting in 12-Ft.
- Restore instrumentation
- Conduct test
- Analyze results
- Prepare final report

Basic Model



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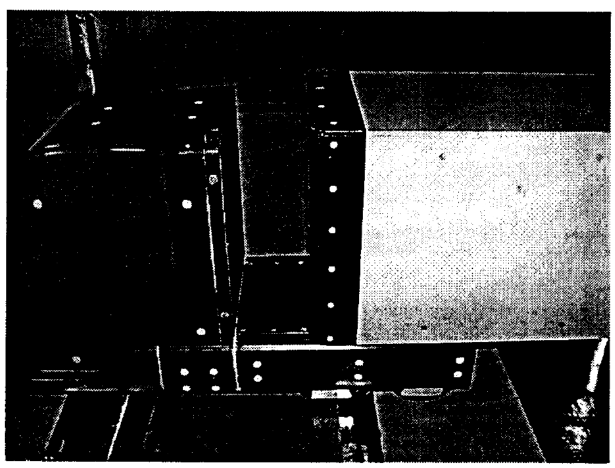
Basic Model - Gap



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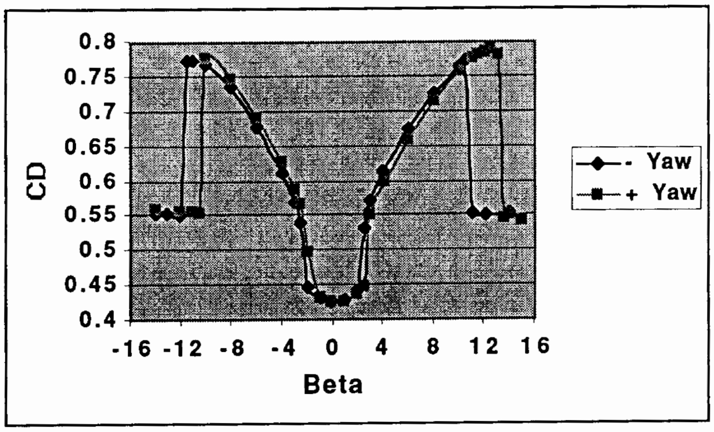
Basic Model - Hysteresis



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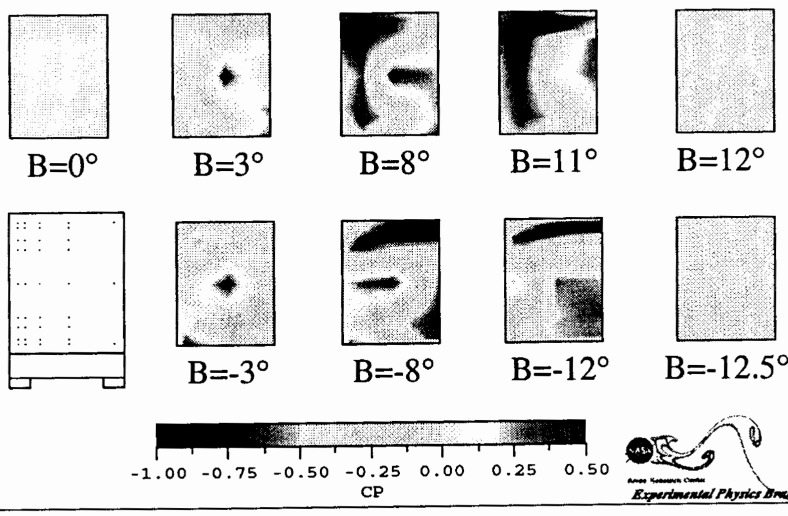
Basic Model
Tractor Rear Pressures



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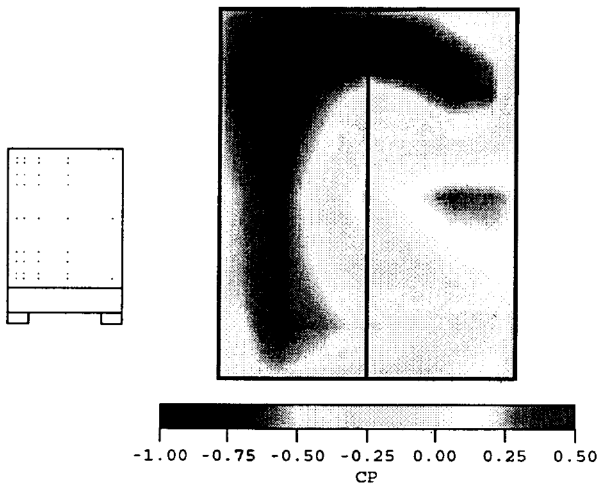
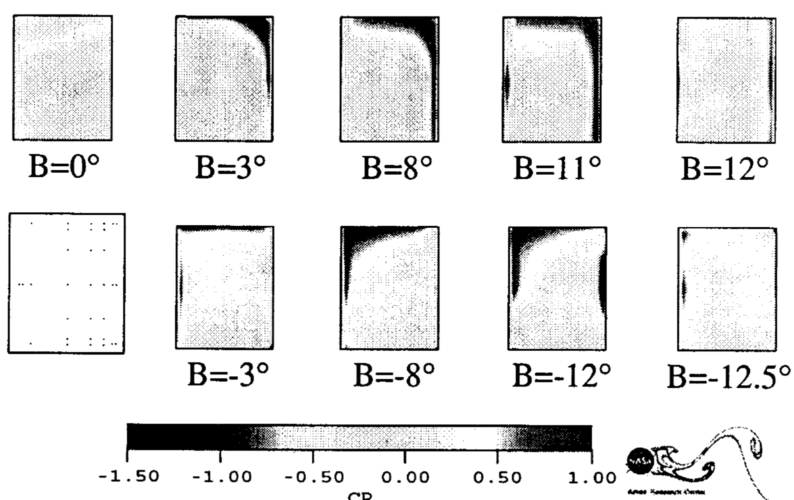
Composite TractorPressures for Beta=10°



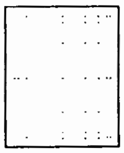
Experimental Physics Branch

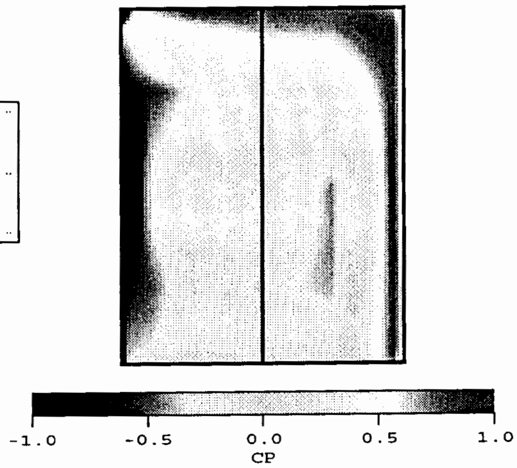
Basic Model Trailer Front Pressures



Experimental Physics Branch

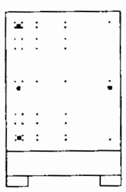
Composite TrailerPressures for Beta=10°

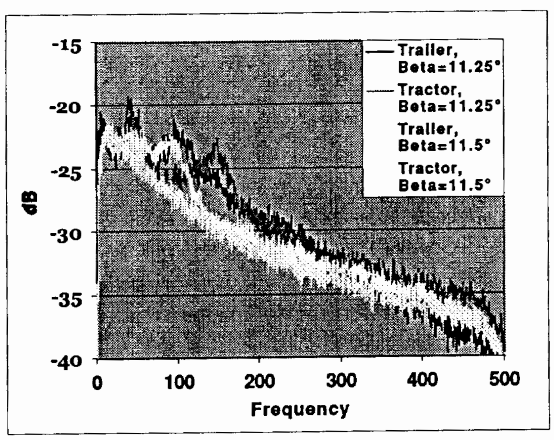




Experimental Physics Branch

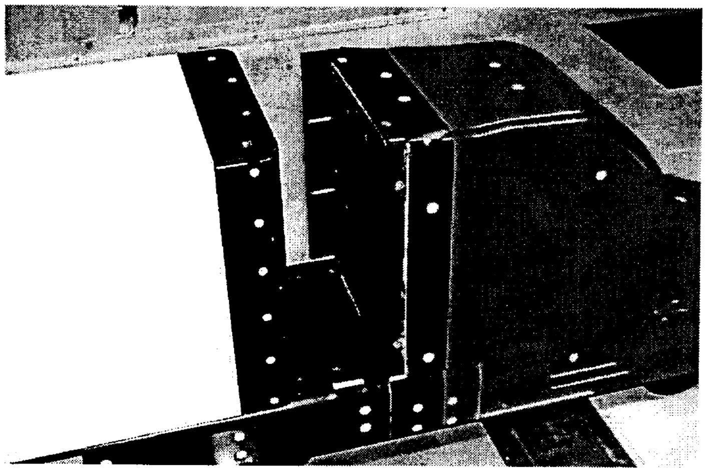
Basic Model - Spectra Gap Data



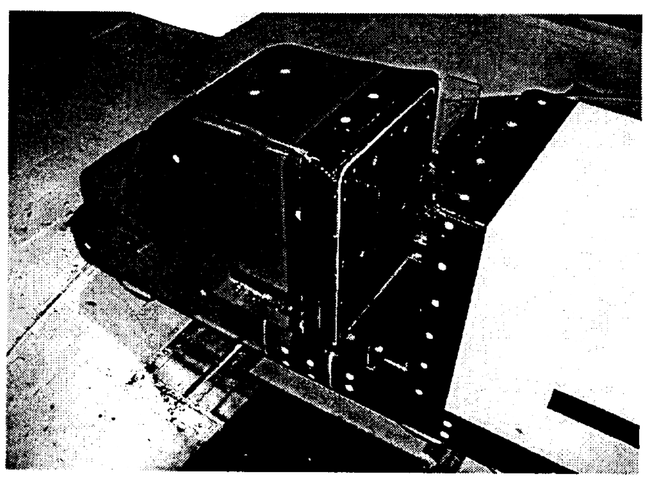


Experimental Physics Branch

Side Extenders

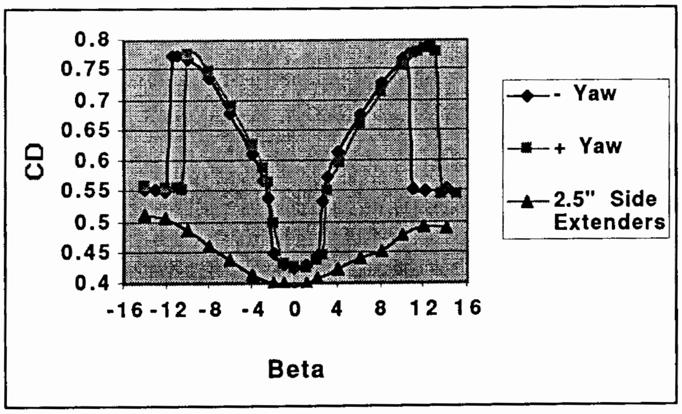


Glass Side Extenders



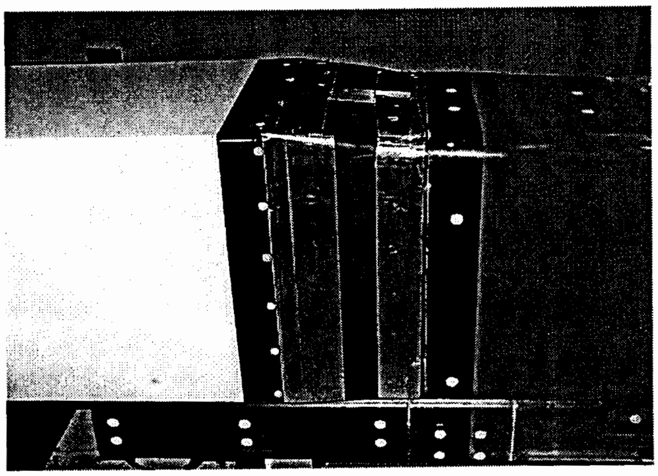
Ames Research Center
Experimental Physics Branch

Side Extenders



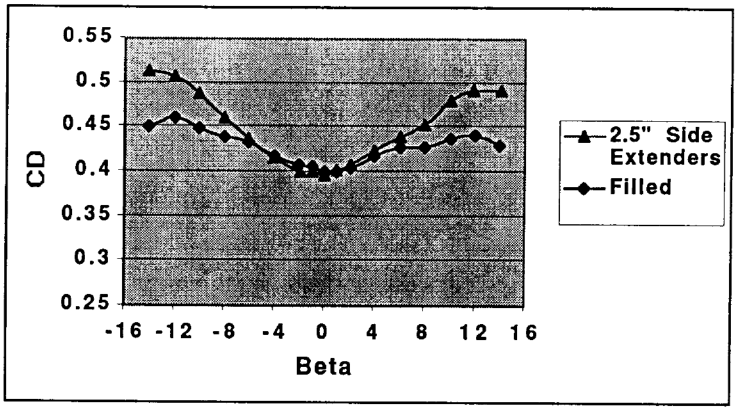
Experimental Physics Branch

Filled Gap



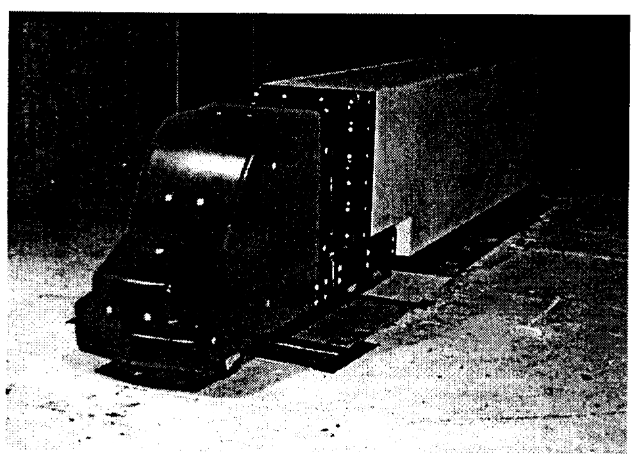
Experimental Physics Branch

Filled Gap



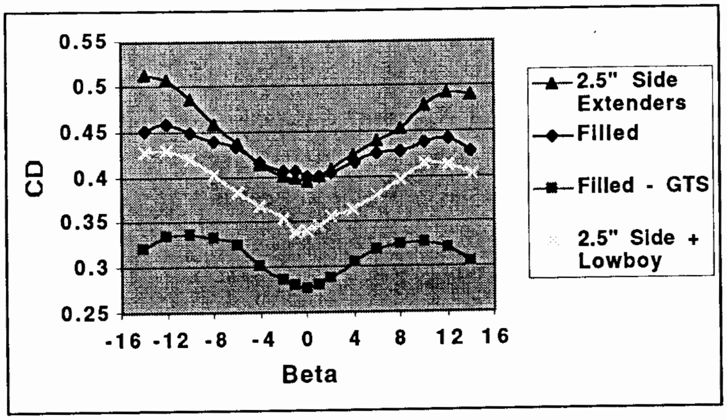
Experimental Physics Branch

Lowboy Trailer



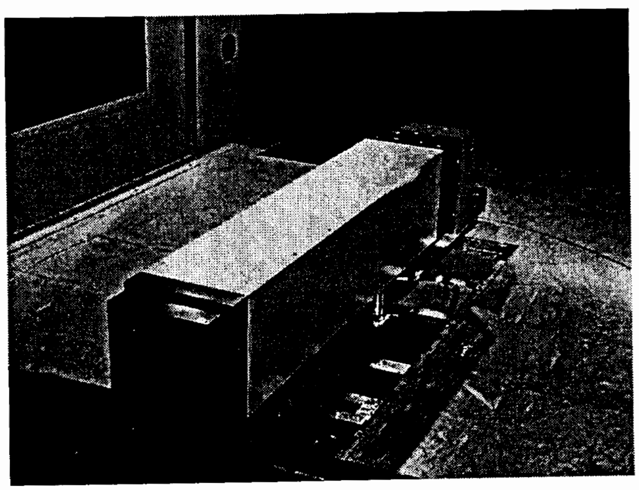
Experimental Physics Branch

Lowboy Trailer



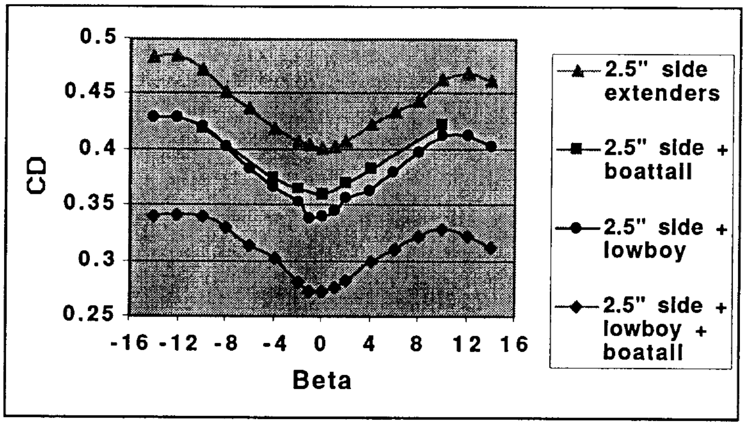
Experimental Physics Branch

Boattail



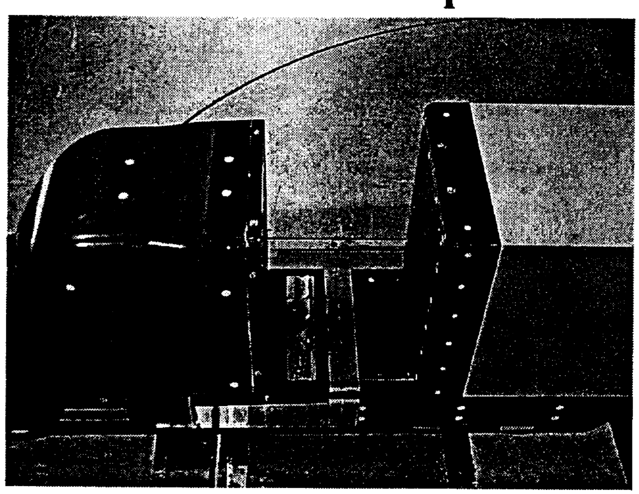
Experimental Physics Branch

Boattail



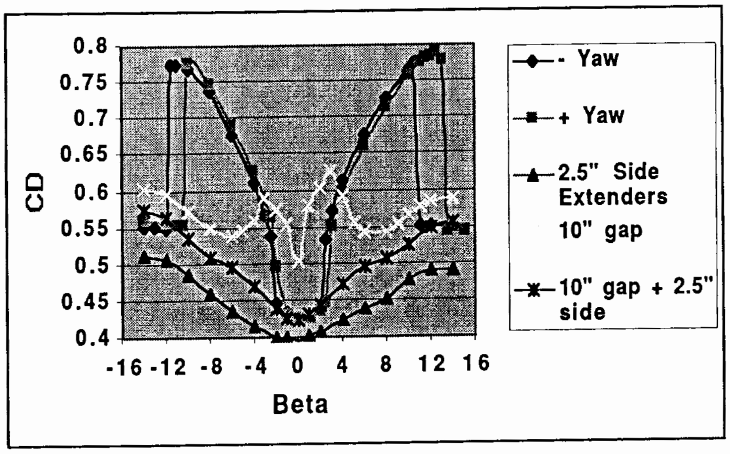
Experimental Physics Branch

Extended Gap



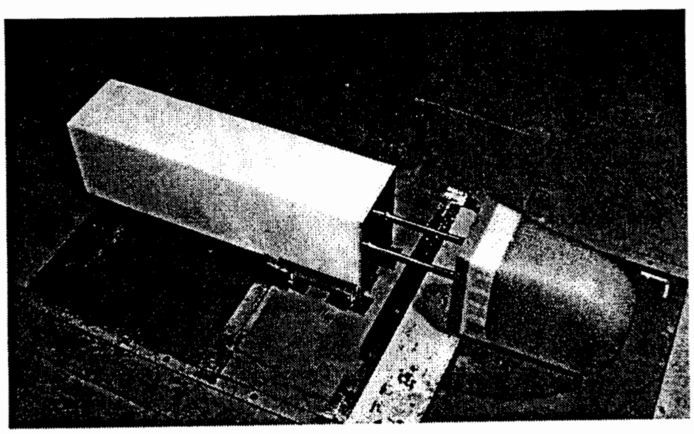
Experimental Physics Branch

Extended Gap



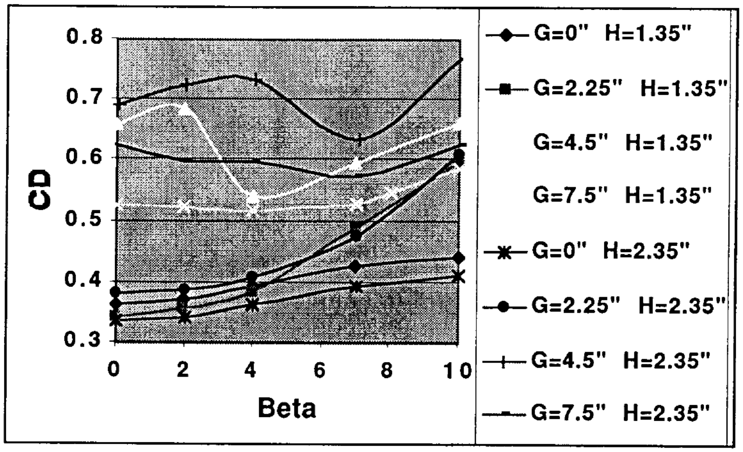
Experimental Physics Branch

USC Model



Experimental Physics Branch

USC Gap and Height



Experimental Physics Branch

Three-component PIV of Generic Conventional Model (GCM) Truck Test in 7x10 and12-Ft.

JT Heineck, Stephen Walker
jheineck@mail.arc.nasa.gov
650-604-0868

Experimental Physics Branch

Summary of PIV Efforts

1998: Army/NASA 7x10

- GCM Wake flow, with and without boattail device, 0 and 10 deg, 7 planes, 3 Reynolds conditions

2001: Army/NASA 7x10

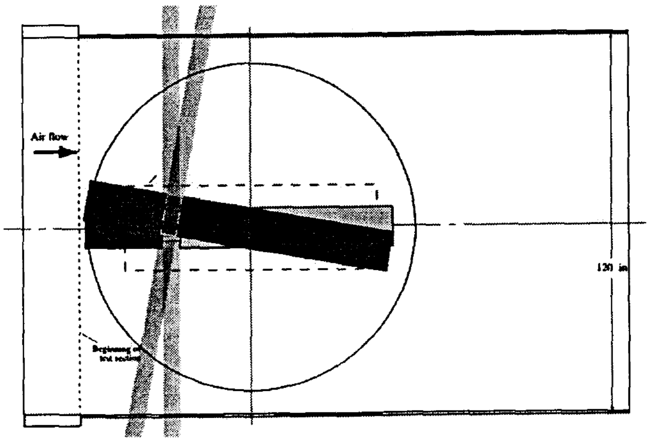
- GCM Gap flow, with and without side extenders, 0 and 10 deg yaw, 3 planes
- GCM Wake flow, with and without boattail device, 0 and 10 deg, 3 planes
- 1 Reynolds Condition

2002: NASA 12-foot Pressure Wind Tunnel

- GCM Gap flow, with and without side extenders, 0, 5 and 10 deg yaw, 3 planes
- GCM Wake flow, with and without boattail device, 0 and 10 deg, 3 planes
- 2 Reynolds Conditions

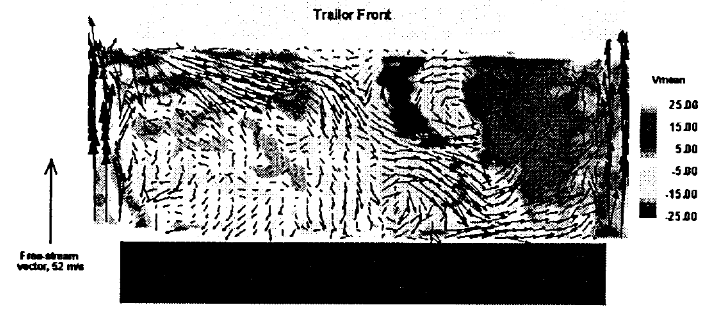
Experimental Physics Branch

PIV in 7 x 10 of GCM – Gap Study



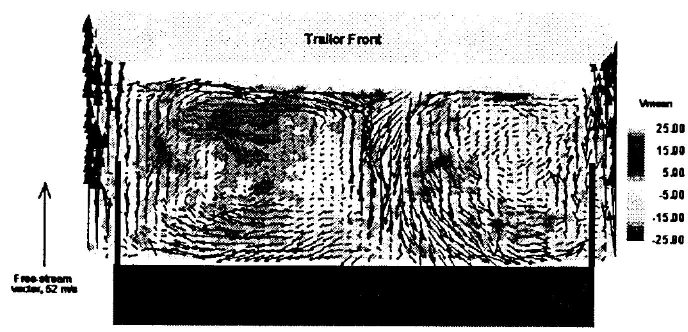
Experimental Physics Branch

50% gap height, 0 deg. yaw, no side extenders
50 vector fields animated

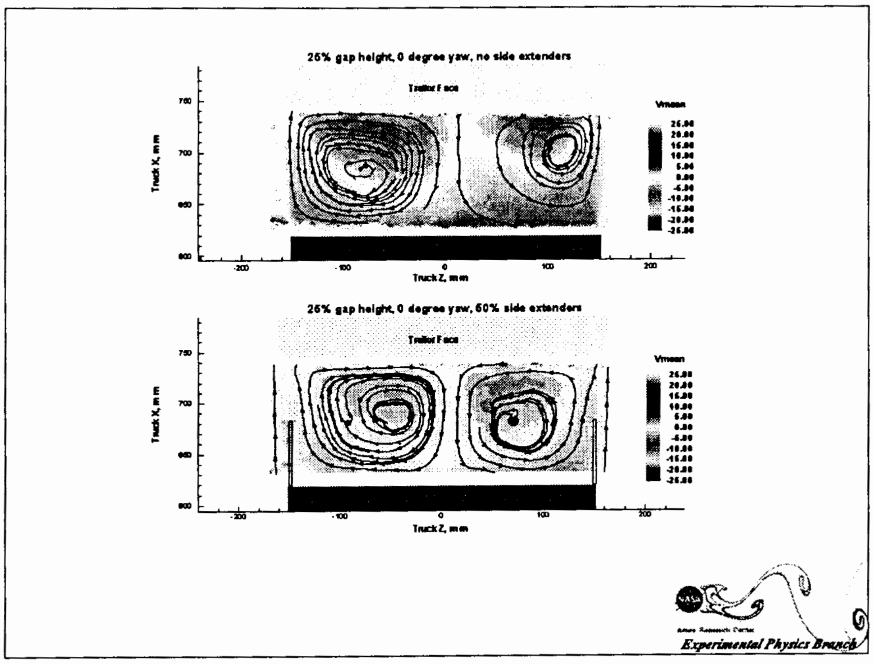


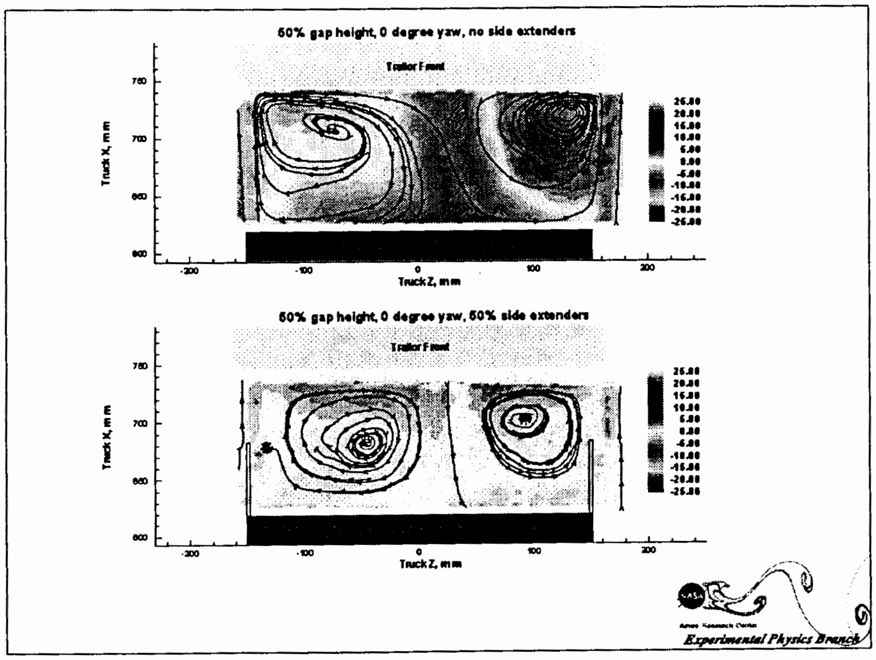
Experimental Physics Branch

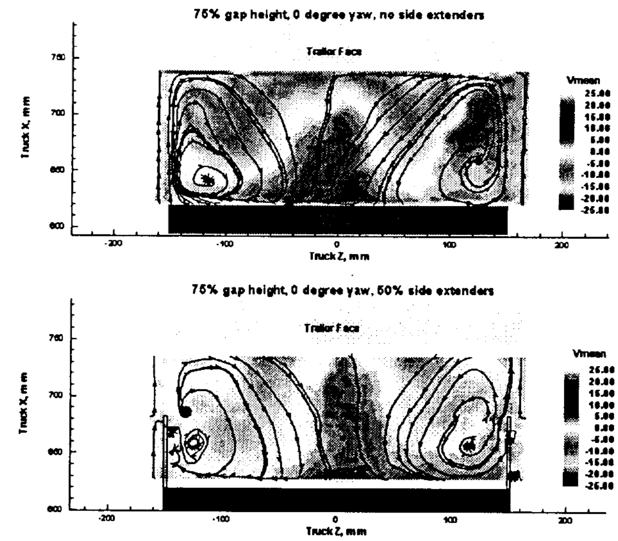
50% gap height, 0 deg. yaw, 50% side extenders
50 vector fields animated



Experimental Physics Branch

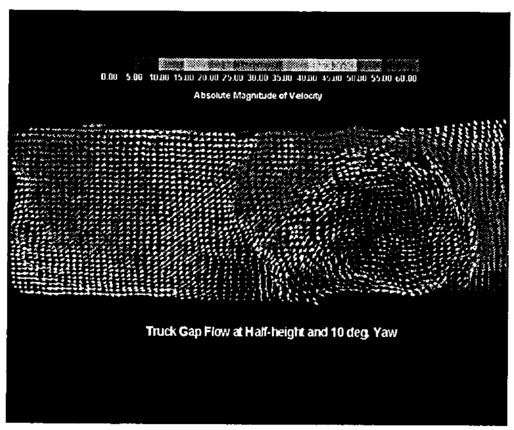

25% gap height, 0 degree yaw, no side extenders
Trailer Face
Truck X, mm
Truck Z, mm
Vmean
25% gap height, 0 degree yaw, 50% side extenders
Trailer Face
Truck X, mm
Truck Z, mm
Vmean
Experimental Physics Branch


50% gap height, 0 degree yaw, no side extenders
Trailer Front
Truck X, mm
Truck Z, mm
50% gap height, 0 degree yaw, 50% side extenders
Trailer Front
Truck X, mm
Truck Z, mm
Experimental Physics Branch

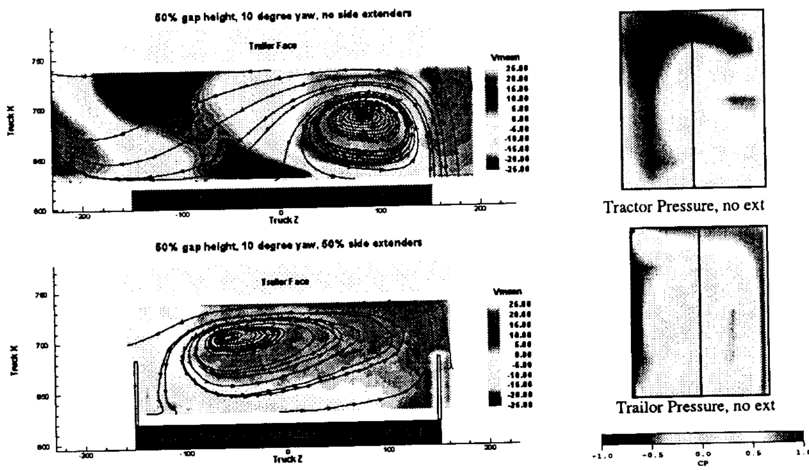


Experimental Physics Branch

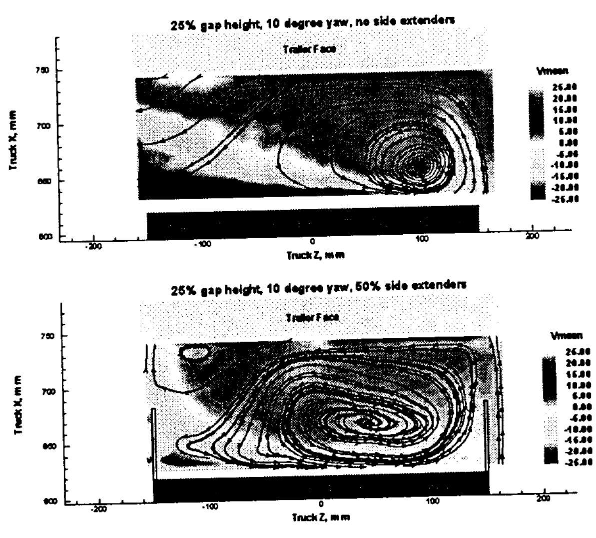
Animation of 100 Vector Fields, 50% Height in Gap, 10 deg Yaw



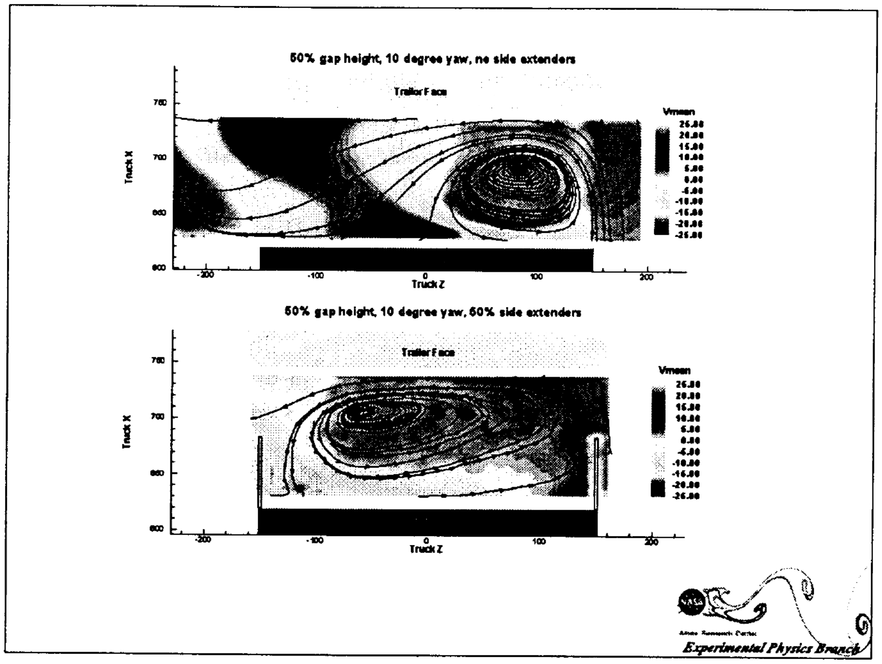
Experimental Physics Branch



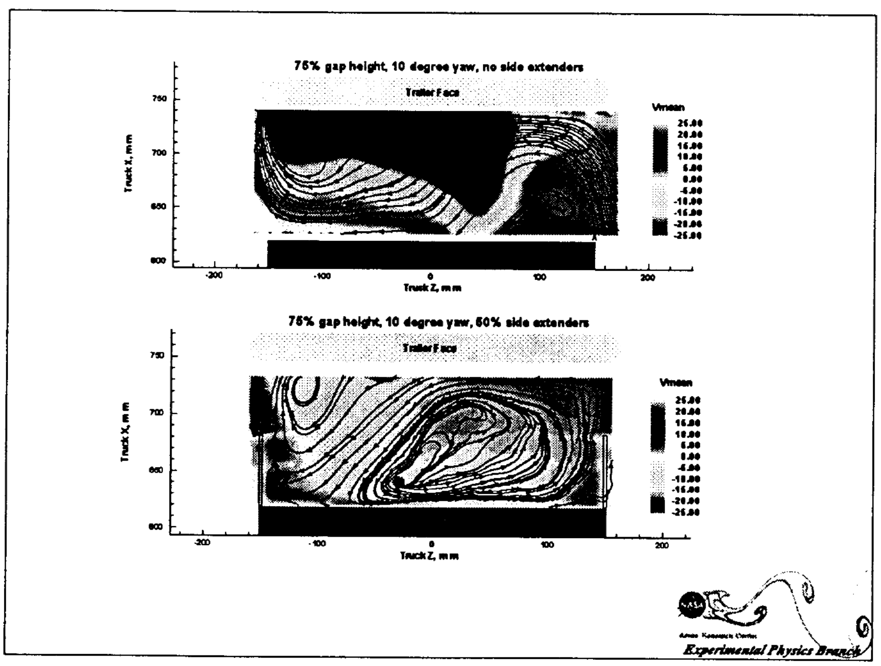
Experimental Physics Branch



Experimental Physics Branch

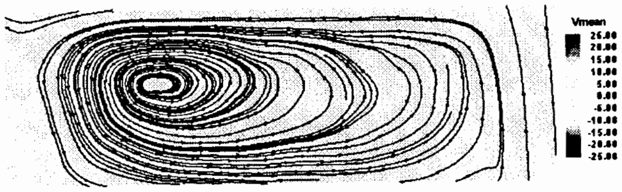


50% gap height, 10 degree yaw, no side extenders
Trailer Face
Truck X
Truck Z
Vmean
50% gap height, 10 degree yaw, 60% side extenders
Trailer Face
Truck X
Truck Z
Vmean
Ames Research Center
Experimental Physics Branch

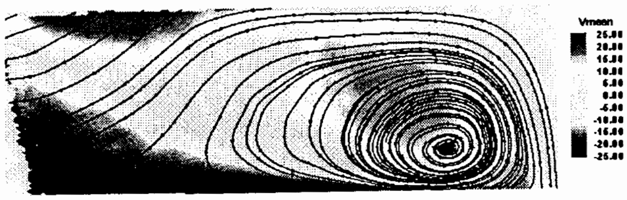


75% gap height, 10 degree yaw, no side extenders
Trailer Face
Truck X, mm
Truck Z, mm
Vmean
75% gap height, 10 degree yaw, 60% side extenders
Trailer Face
Truck X, mm
Truck Z, mm
Vmean
Ames Research Center
Experimental Physics Branch

25% gap height, 11 deg Yaw, low-drag state



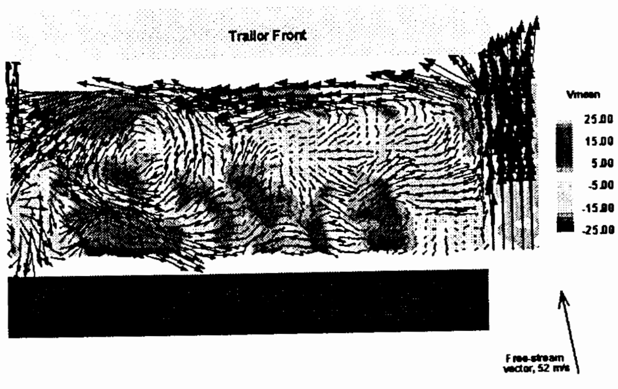
25 % gap height, 10 deg Yaw, high-drag state



Ames Research Center

Experimental Physics Branch

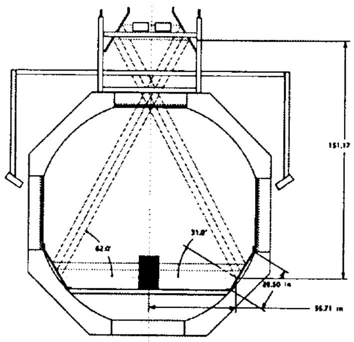
25% gap height, 11 deg. yaw, no side extenders
35 vector fields animated



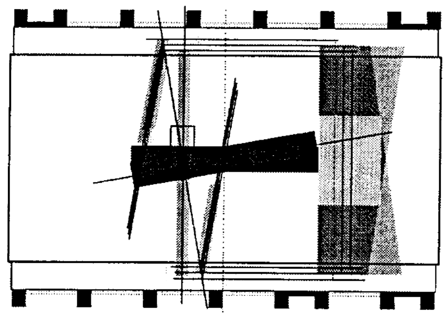
Ames Research Center

Experimental Physics Branch

PIV at the 12 foot Pressure Tunnel



Upwind view



Top view

Experimental Physics Branch

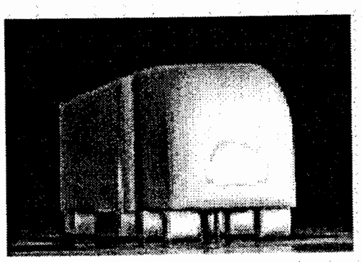
USC Presentation for
DOE Office of Transportation Technology
Office of Heavy Vehicle Technology

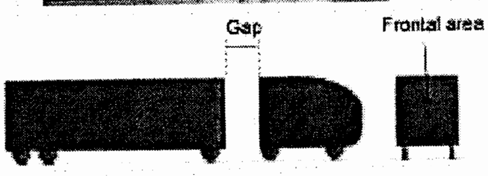
M. Hammache, staff
T.Y. Hsu, staff
D. Arcas, PhD student
D. Monnesinghe, MS student
D. Lazzara, student
C. Radovich, student
R. Blackwelder, staff
F. Browand, staff
P. Lissaman, staff

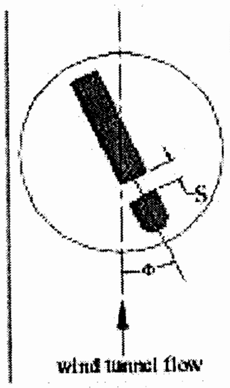
USC University of Southern California
Ground Vehicle Aerodynamics Laboratory

Aerodynamic Forces on Truck Models, Including Two Trucks in Tandem

Mustapha Hammache, Mark Michaelian, Fred Browand,
SAE paper No. 2002-01-0530 (Force data for tractor-trailer available on CD)





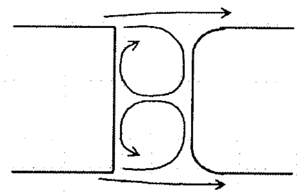


The Structure of Turbulent flow in the Gap Between Tractor and Trailer

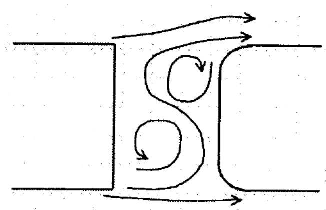
Mustapha Hammache, Fred Browand

Flow Patterns in the Gap

- Small gap

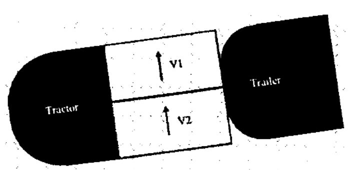


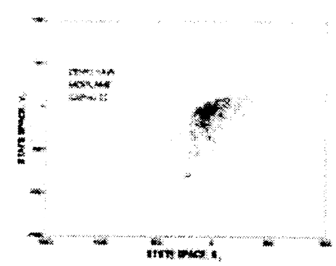
- Critical gap

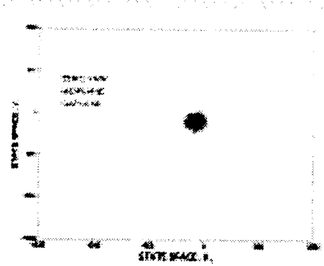


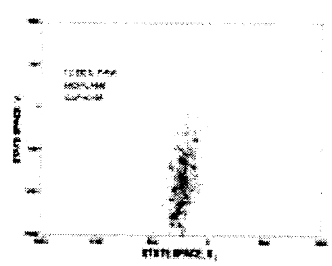
The Structure of Turbulent flow in the Gap Between Tractor and Trailer

Mustapha Hammache, Fred Browand



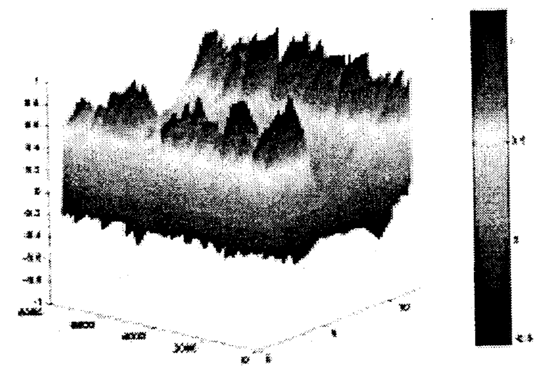






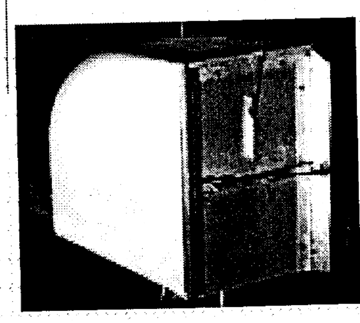
Instantaneous Pressure Measurements of Turbulent Flow in the Gap of a Tractor-Trailer Vehicle

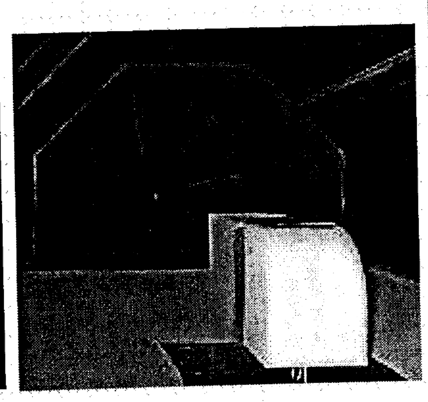
David Lazzara, Submitted, AIAA Student Paper Competition, San Luis Obispo, April 2002



Effect of Cab Extender Geometries on the Drag of a Model Tractor-Trailer

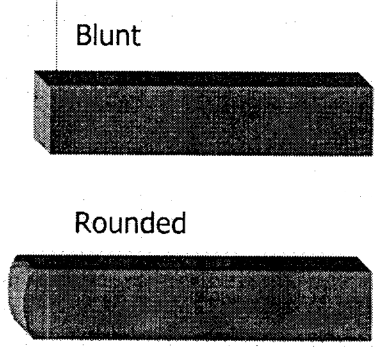
Devinda Moonesinghe, Charles Radovitch

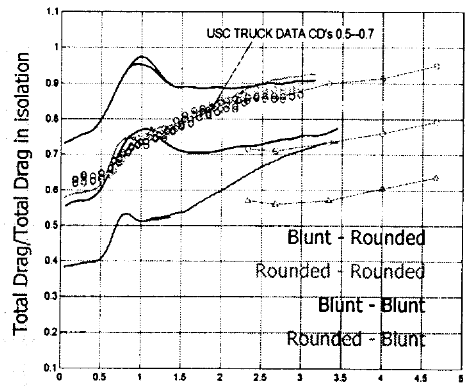




The Limits of Drag Behavior for Two Bluff Bodies in Tandem

Fred Browand & Mustapha Hammache,
14th USNCTAM, The Roshko symposium on Turbulent Structure and Flow Control, June 23-25, Blacksburg, VA



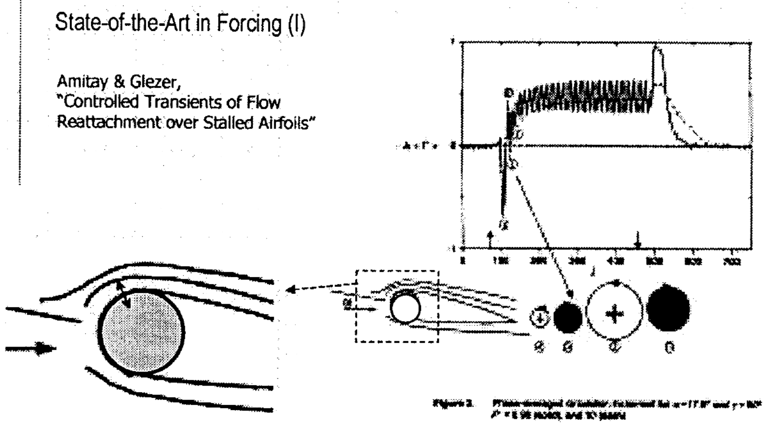


Base Geometry Modifications and Acoustic Forcing to Reduce Drag

Tsun-Ya Hsu, Mustapha Hammache

State-of-the-Art in Forcing (I)

Amitay & Glezer,
"Controlled Transients of Flow Reattachment over Stalled Airfoils"

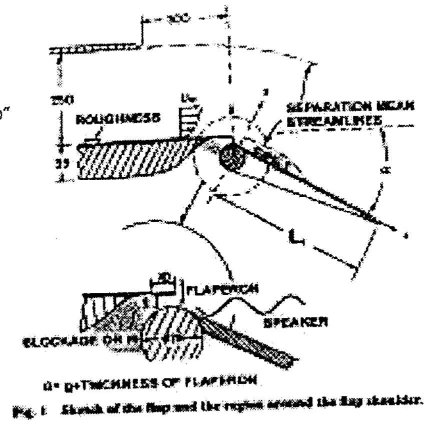


Base Geometry Modifications and Acoustic Forcing to Reduce Drag

Tsun-Ya Hsu, Mustapha Hammache

State-of-the-Art in Forcing (II)

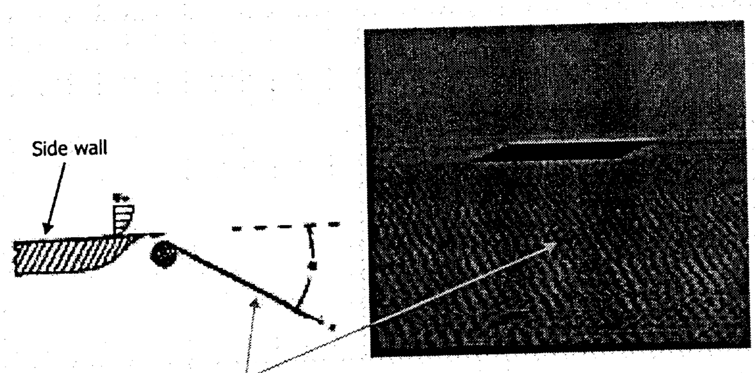
Nishri & Wygnanski,
"Effects of Periodic Excitation on Turbulent Flow Separation from a Flap"



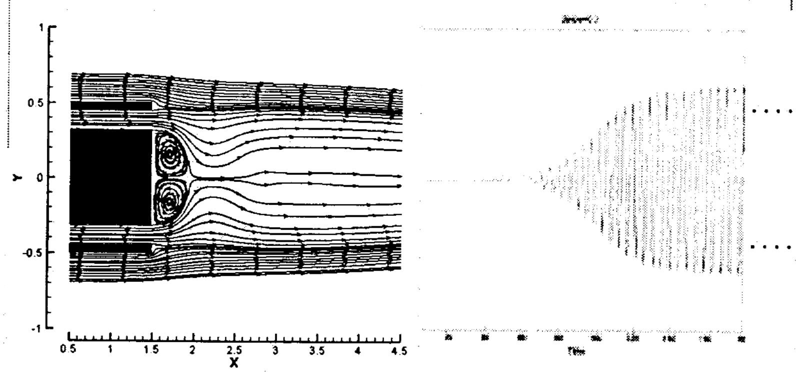
Base Geometry Modifications and Acoustic Forcing to Reduce Drag

Tsun-Ya Hsu, Mustapha Hammache

Current Forcing Design at USC



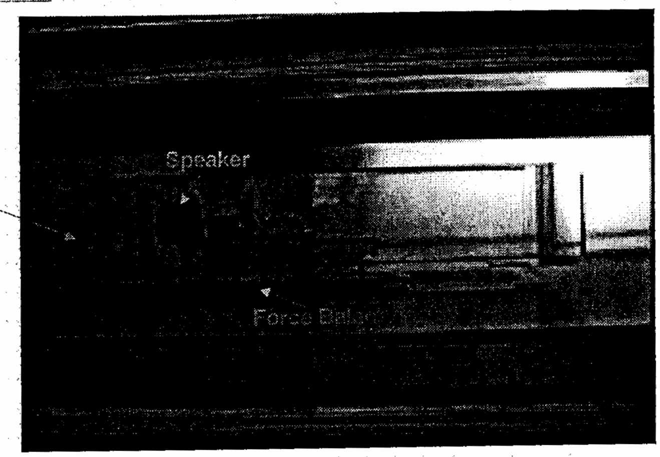
2-D Numerical Models of the Base Flow Region Subjected to Modifications in Geometry or Small Addition or Removal of Mass
Diego Arcas



Contents

- Experimental Apparatus
- Experimental Conditions
- Results
- Summary & Future Study

Experimental Apparatus

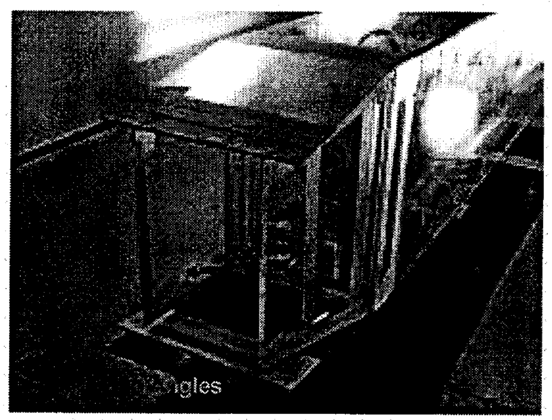


USC GROUND VEHICLE AERODYNAMICS LABORATORY

Experimental Apparatus (Cont'd)

USC GROUND VEHICLE AERODYNAMICS LABORATORY

Experimental Apparatus (Cont'd)



USC GROUND VEHICLE AERODYNAMICS LABORATORY

Experimental Details

- Free Stream Velocity, U = 13 to 20 m/s
- $A = 0.0535\ m^2$
- $Re_{sqrt(A)} = 2.8 \times 10^5$ to 3.2×10^5
- Flap lengths: 14 to 24 cm
- Ramp angles: 0^o, 5^o, 10^o
- Square wave with frequency, f = 60 to 120 Hz
- Gap width for the jet, g = 1 mm

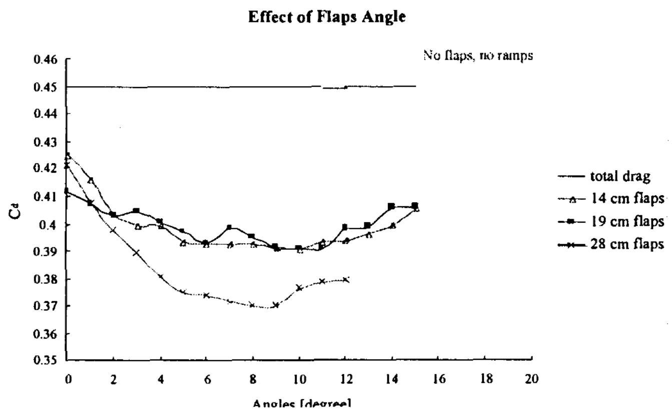
USC GROUND VEHICLE AERODYNAMICS LABORATORY

Experimental Results

- Without Forcing:
  - Drag measurements for varying flap angles
  - Effect of flap lengths on drag coefficients
- With Forcing:
  - Drag measurements for varying forcing frequency

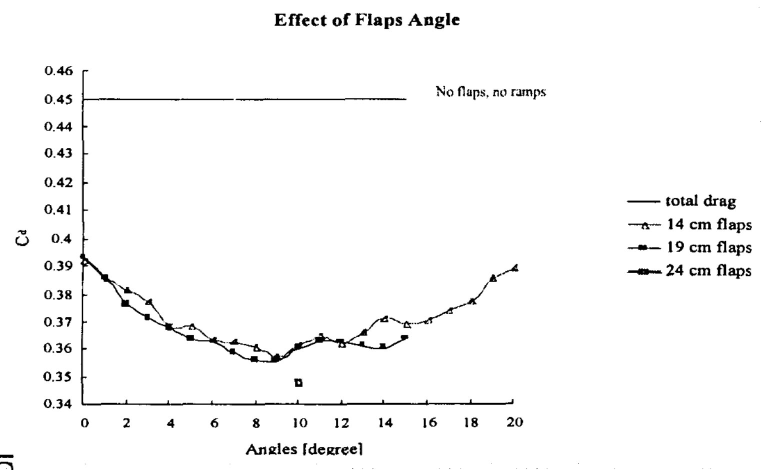
Without Forcing

Effect of Flaps Angle on C_d: Flaps without Ramps



USC GROUND VEHICLE AERODYNAMICS LABORATORY

Effect of Flaps Angle on C_d: Flaps with 10° Ramps

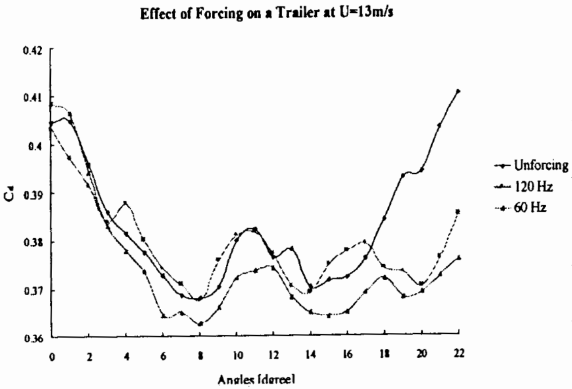


USC GROUND VEHICLE AERODYNAMICS LABORATORY

With Forcing

USC GROUND VEHICLE AERODYNAMICS LABORATORY

Effect of Forcing Function on C_d: 19 cm Flaps with 15° Ramps , U = 13 m/s



USC GROUND VEHICLE AERODYNAMICS LABORATORY

Summary & Present Study Continued

- Without forcing: 20% saving based on total drag
- Forcing has effect on drag reduction
- Utilizing DPIV technique to further understand the flow characteristics at flap angle around 10 degrees.
- Develop complex waveforms as a forcing function to decrease drag.
- Use experimental results to develop an enhanced 3D model.

USC GROUND VEHICLE AERODYNAMICS LABORATORY

Flow Structure and Drag Reduction in 2-D Wakes with Boat-Tails

A Direct Numerical Simulation of the Basic Flow

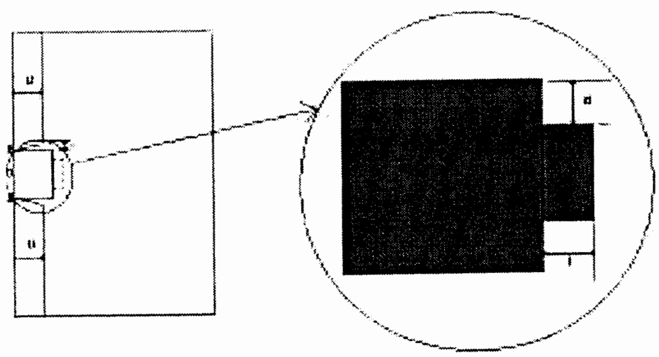
D. R. Arcas, F. K. Browand and L. G.Redekopp
Dept. of Aerospace Engineering
University of Southern California

Objectives:

- To reach an understanding of the basic flow dynamics associated with geometric configurations of minimum drag.
  - Identification of the minimum drag configurations by means of a parametric study.
  - Study of the velocity and pressure fields.
  - Study the possibility of using suction/blowing for drag reduction purposes.

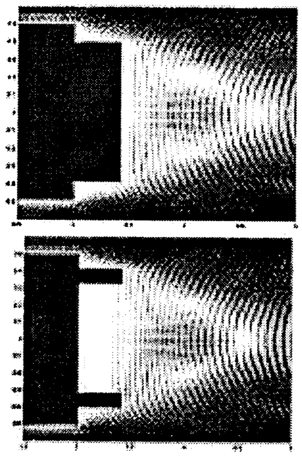
Bluff-body Wake Geometry

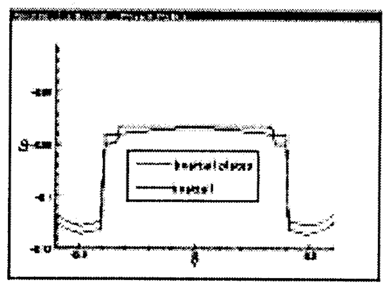
Parameters: $\mathrm{Re} = \frac{U_\infty H}{\nu}$ d, l, δ



Bluff Body Wake:

-Boattail Configuration

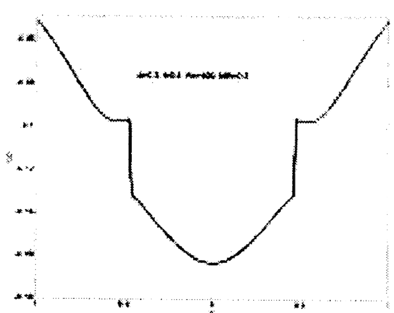




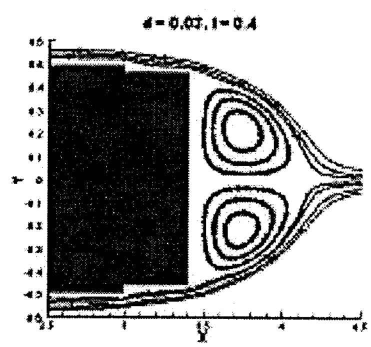
Discrepancies between the *boattail* and the *boattail plates* configurations are minimal in this regime of flow.

d=0.03, l=0.4

Pressure Profile

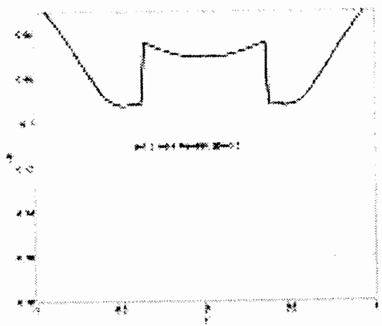


Streamline Pattern

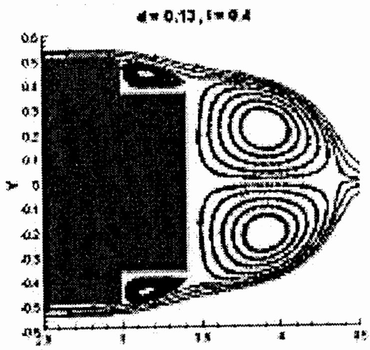


d=0.13, l=0.4 (Optimum case)

Pressure Profile

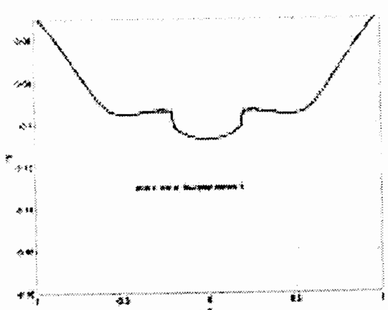


Streamline Pattern

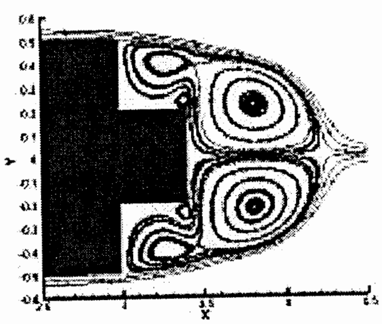


d=0.3, l=0.4

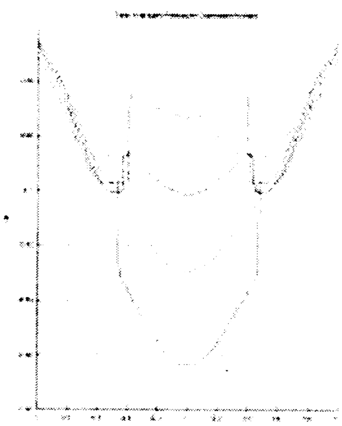
Pressure Profile



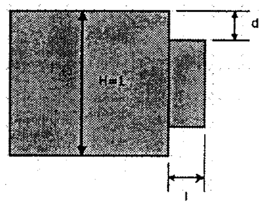
Streamline Pattern



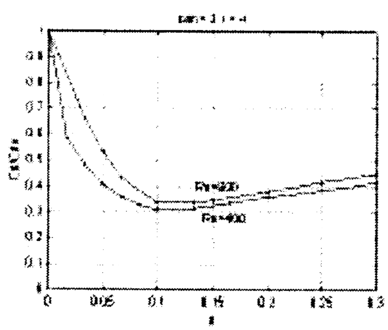
Pressure Profiles:

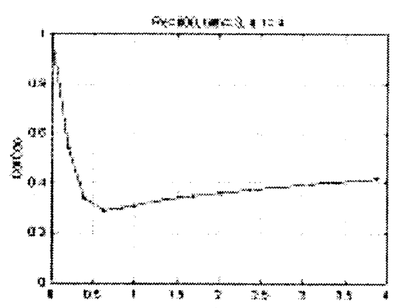


Rising Pressure		Dropping Pressure	
d=.03	————	d=.10	- - - - -
d=.05	————	d=.20	- - - - -
d=.06	————	d=.30	- - - - -
d=.10	————		



Influence of Different Parameters
Drag Reduction



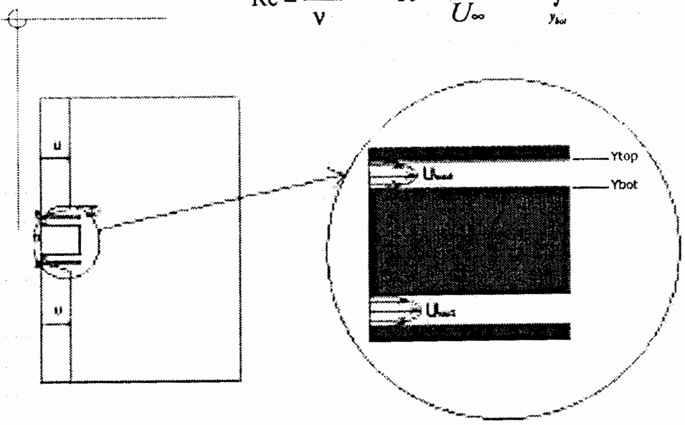


Minimum Value of Drag with, d	Minimum Value of Drag with , l
d_{min}~0.12	l_{min}~0.65

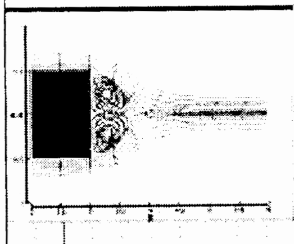
$(l/d)_{empirical}$~6

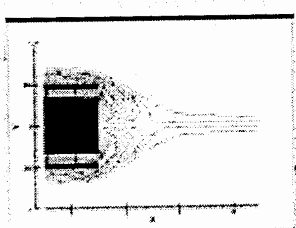
Bluff-body Wake Geometry

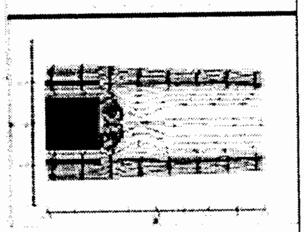
Parameters: $\mathrm{Re} = \frac{U_j D}{\nu}$ $R = \frac{U_j}{U_\infty}$ $q = \int_{y_{bot}}^{y_{top}} U_{suct}(y)dy$ δ



Wake Manipulation by Means of Suction/Blowing



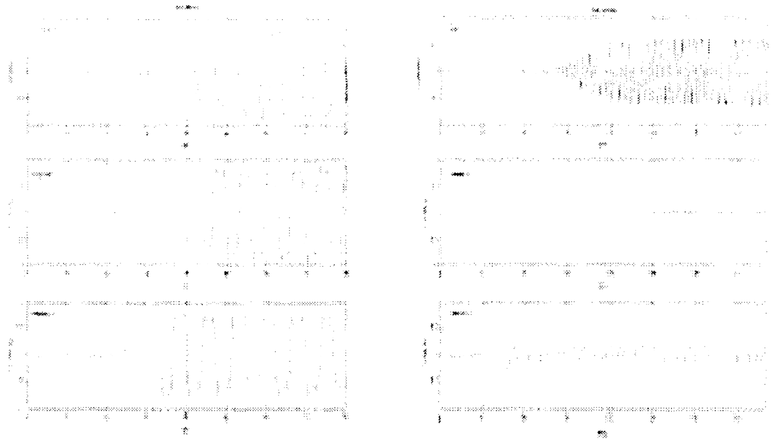




Differences in the Time-Averaged Velocity Field without forcing and with suction/blowing .
(Suction Velocity, Us=0.9, Re=800, δ=.3)

Suction / Blowing

Suction | Blowing



Time history of the cross-stream velocity signal

Conclusions

- A significant amount of drag reduction can be achieved by appropriate modification of the base geometry of a blunt body.
- The high pressure region at the trailing edge of the boattail seems to be associated with the change of streamline curvature in the notch-region.
- Suppression of vortex shedding can effectively be achieved by means of blowing fluid into the wake.

Experimental Summary

• Supplying long flaps (flap length ≈ $\sqrt{A}$) to the model truck base results in a decrease in drag of about 20%, referenced to the drag of the model having no flaps.

• Referenced to the total drag of a more faithful truck model (wheels, etc.), the drag decrease would be about 10%.

• Referenced to the base drag alone--the most useful reference--the drag decrease is about 40%.

•A preliminary application of acoustic forcing--when added to flap—can produce an additional decrease in drag (referenced to the base drag).

• Acoustic forcing could be made effective with shorter flaps.

Near-Term Experimental Tasks

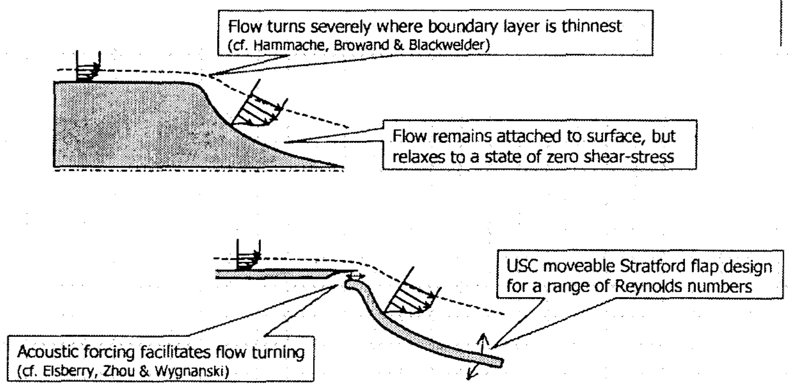
• Pay particular attention to much shortened flap lengths.

• Allow the four flaps to articulate, and allow systematic variation of flap angle, forcing frequency and forcing amplitude.

• Investigate more complex (quasi periodic) wave forms (c.f. Amitay & Glezer, "Controlled Transients of Flow Reattachment over Stalled Airfoils").

• Investigate Stratford-ramp flap shapes
(c.f. Hammache, Browand & Blackwelder, "Whole-field velocity measurements around an axisymmetric body with a Stratford-Smith pressure recovery", *JFM*, in press).

Stratford Ramp Applied to Trailer Base



Numerical Modeling

- 2-D, low Reynolds number computations predict that boat-tail gives an overall base drag reduction of about 60-70%.

- *Preliminary* results also demonstrate that strong wake oscillations associated with global wake- mode instabilities can be suppressed by the application of blowing and/or suction.

Near-Term Numerical Tasks

- Perform numerical calculations to include periodic, zero mass flux blowing and more realistic flap geometry so as to make comparisons with our existing experimental results.

- *Continue to define the limits of possible base drag reductions.*

Suggested Group Tasks

- Modify LES/DES codes to allow introduction of blowing and suction--including periodic, zero net mass flow perturbations, so as to realize comparisons with our experiments.

- Numerically explore the limits of realistic base drag reduction for high Reynolds number flow and 3-D geometry.

- Provide for experimental verification at high Reynolds numbers.

Georgia Tech Research Institute

Novatek, Inc
PROTOTYPE DESIGN AND FABRICATION

VOLVO
New Roads.

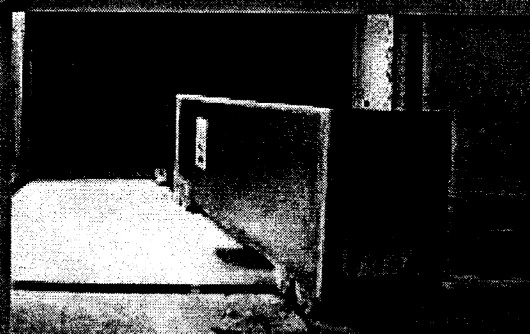
DOE/GTRI Pneumatic Heavy Vehicle Aerodynamic Drag Reduction Program & Tuning Test Results

~DOE Heavy Vehicle Aerodynamic Drag Workshop~

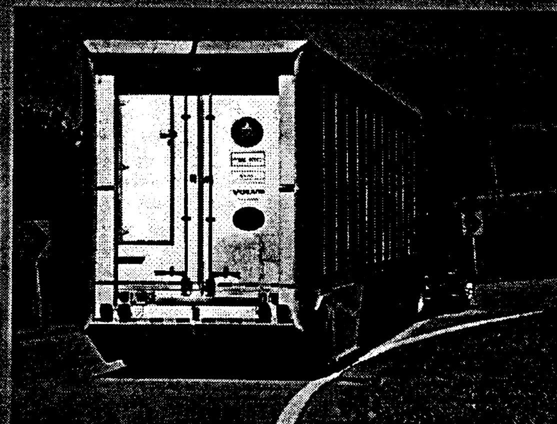
April 3, 2002

by Robert J. Englar, Georgia Tech Research Institute

Application of Advanced Pneumatic Aircraft Technology....



...Through Analytical & Experimental Development ...



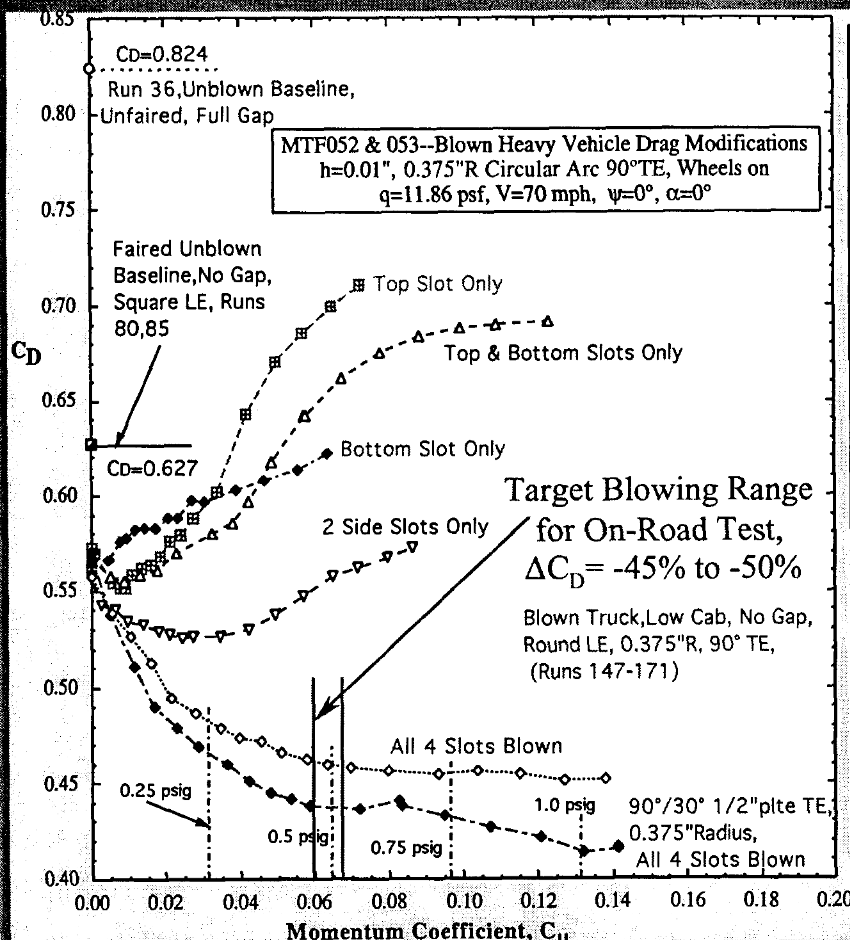
..To On-Road Proof-of-Concept Full-Scale Tests

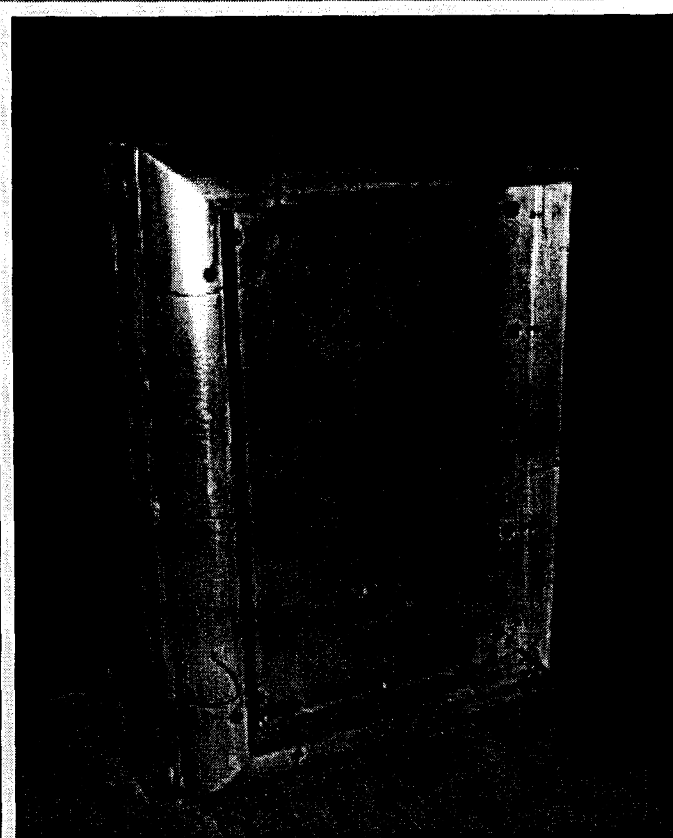
Outline of Presentation

- Introduction: Pneumatic Heavy Vehicle (PHV) Technology
- Pneumatic Heavy Vehicles....Multi-Purpose Aerodynamic Devices:
  - Force & Moment Reductions or Augmentations
  - Fuel Efficiency & Wear Reduction
  - Improved Safety of Operation
  - Increased Stability (Directional & Lateral)
  - Reduced Splash, Spray Turbulence & Hydroplaning
  - No-Moving-Part Integrated Systems
  - Pneumatic Cooling Systems
- Review of Smaller-Scale Wind-Tunnel Model Test Results
- Full-Scale PHV Test Vehicle Design
- Initial Tuning Test of PHV at Volvo Trucks in N.C.
- Continuing Plans
- Conclusions: So, where do we go from here ?...

  ... Or, how do we PROVE this potential on a real vehicle ??

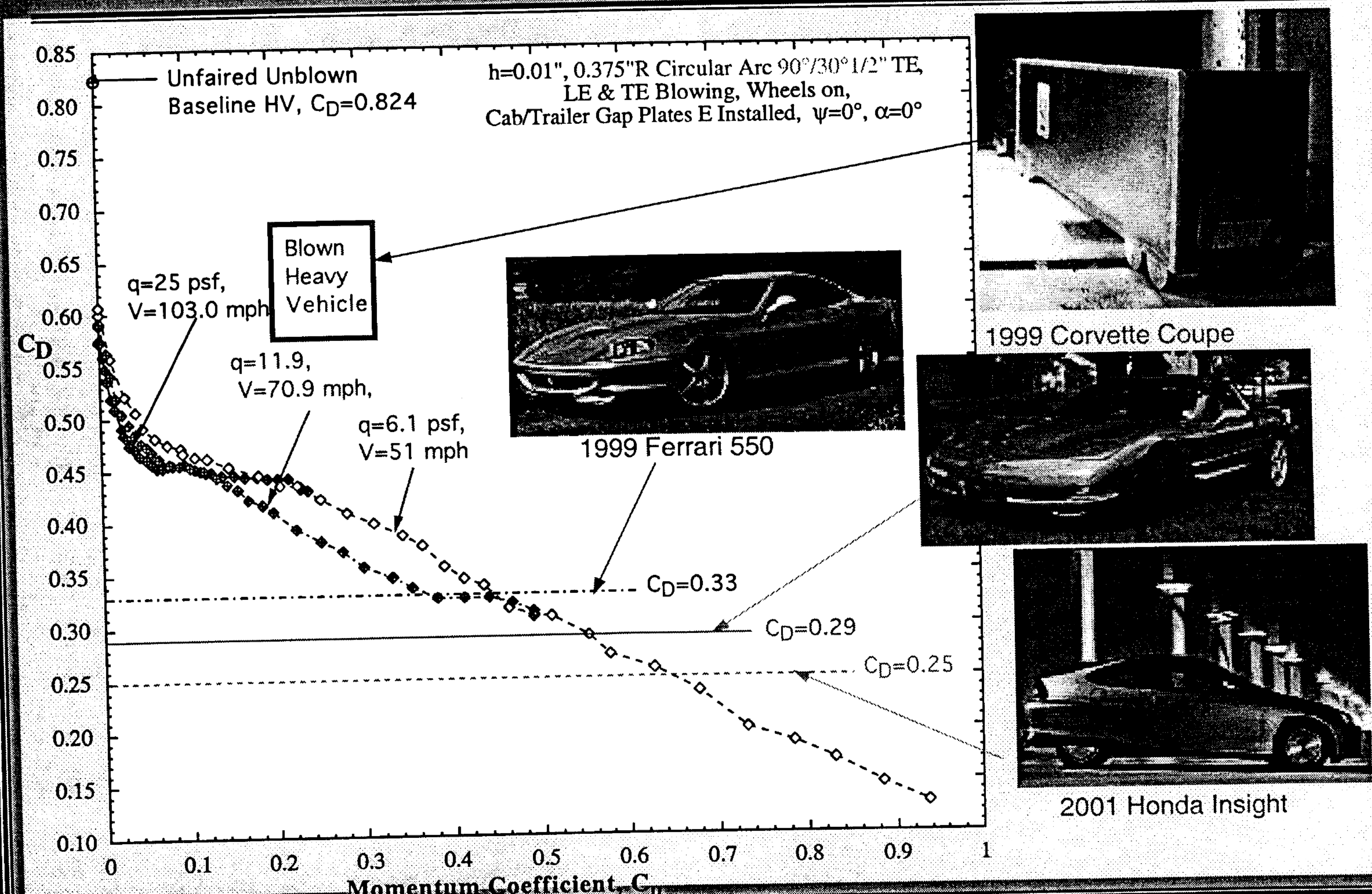
Background: Aero Development & Tunnel Tests at GTRI Showed 50% (or more) Drag Reduction due to Aft Blowing of Various Slots



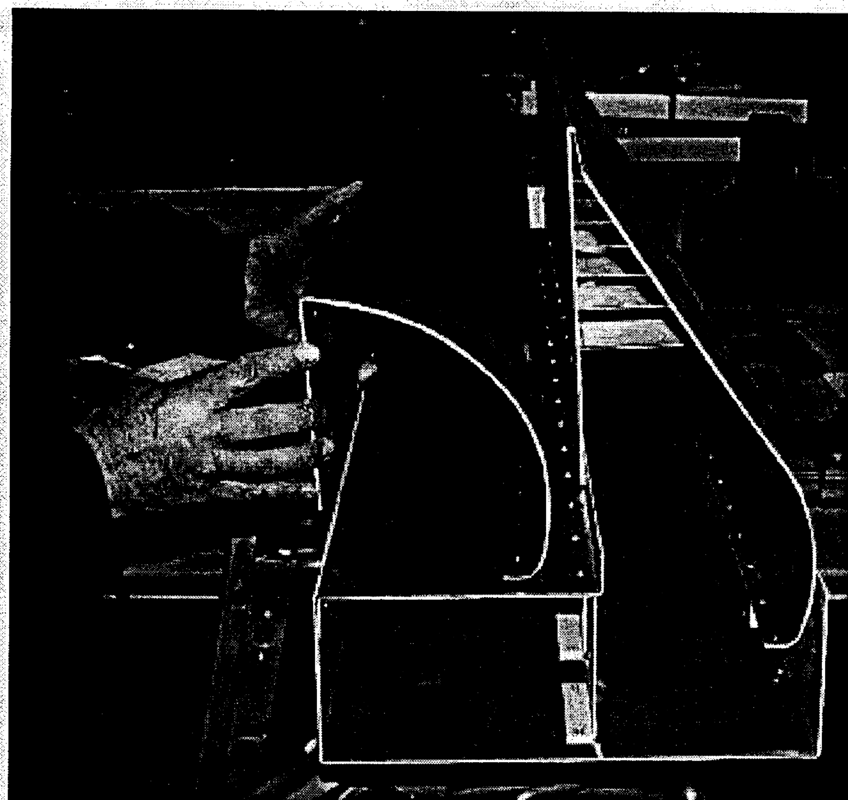


4 Blown Slots on Trailer Rear Doors Of Wind-Tunnel Model

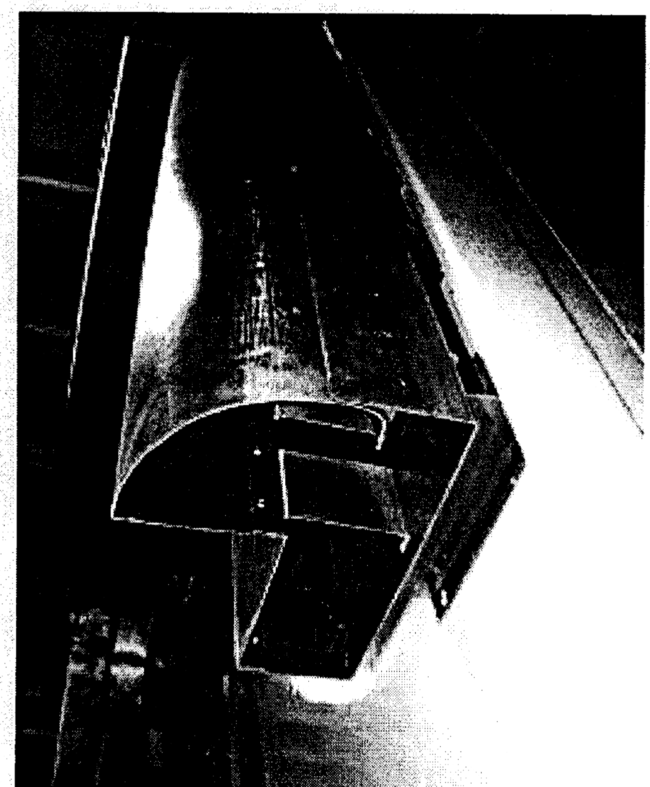
GTRI Extended Tunnel Tests Showed State-of-the-Art Drag Reduction!!



Trailing Edge Turning Surface Geometries

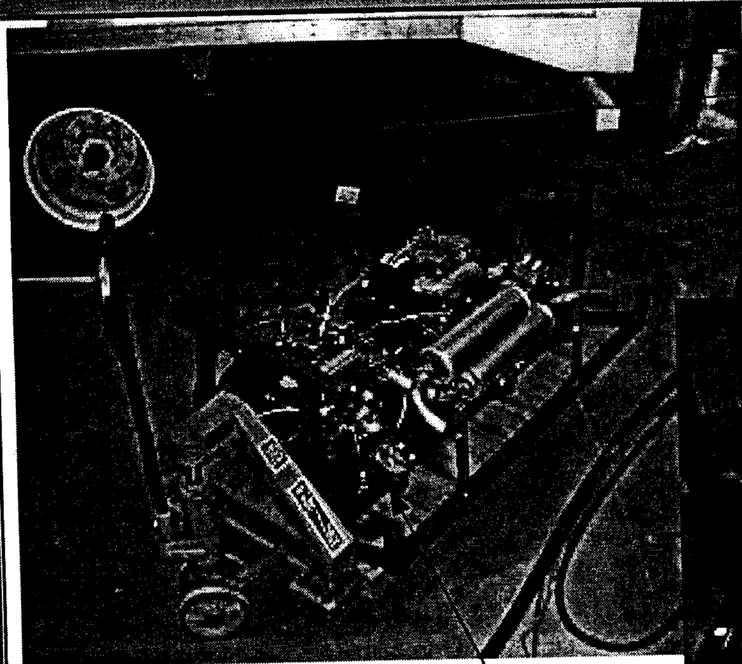


Plenums, Slots and Turning Surfaces,
Showing 90° (left) & 30°

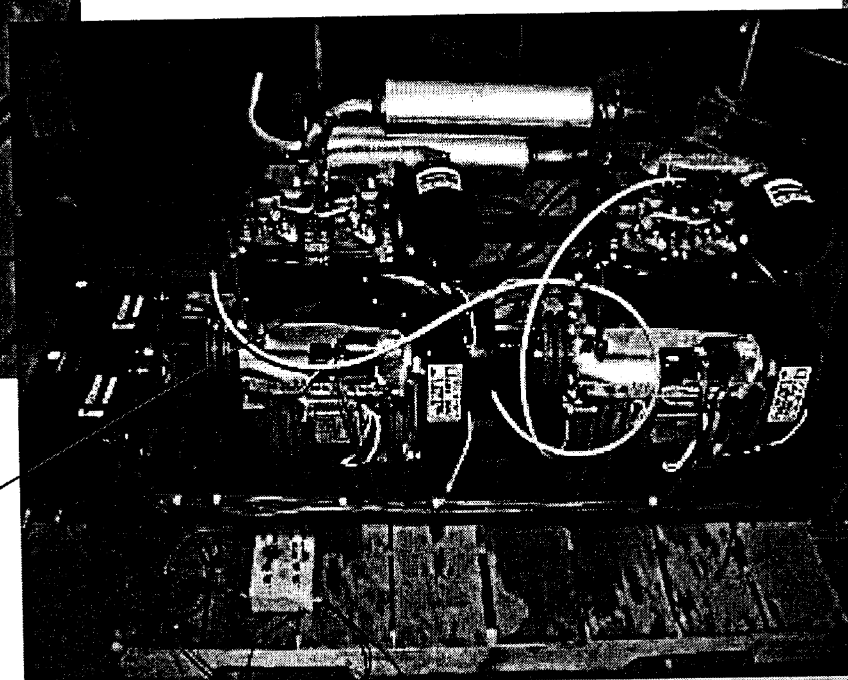


Right Rear Corner, looking up--
90° Side and 30° Top

Air Source Consists of Blowers, Drive Diesels & Mounting Platform

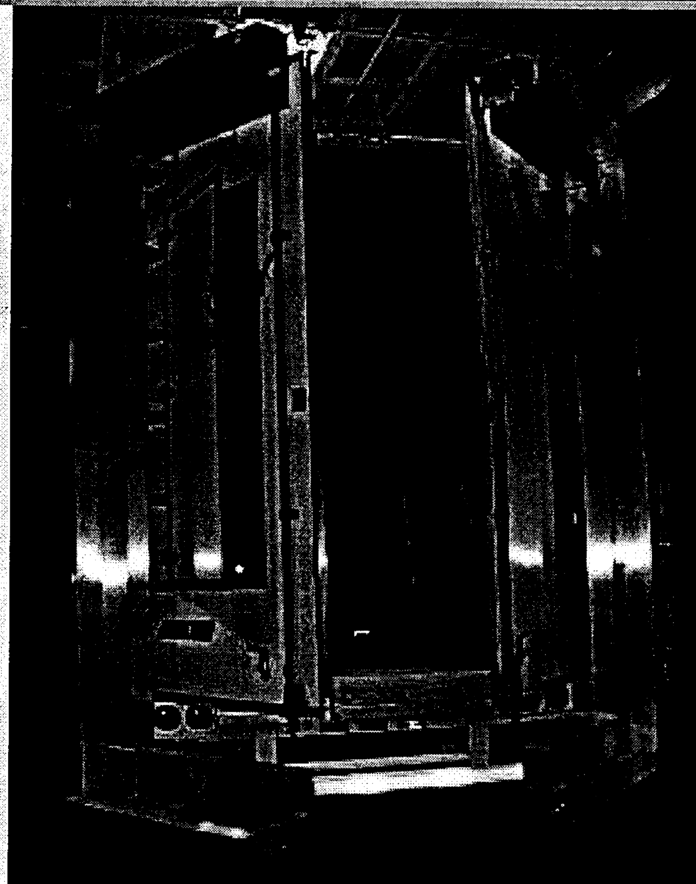


Air Source = New York Blower Co.
Centrifugal Blowers (2)

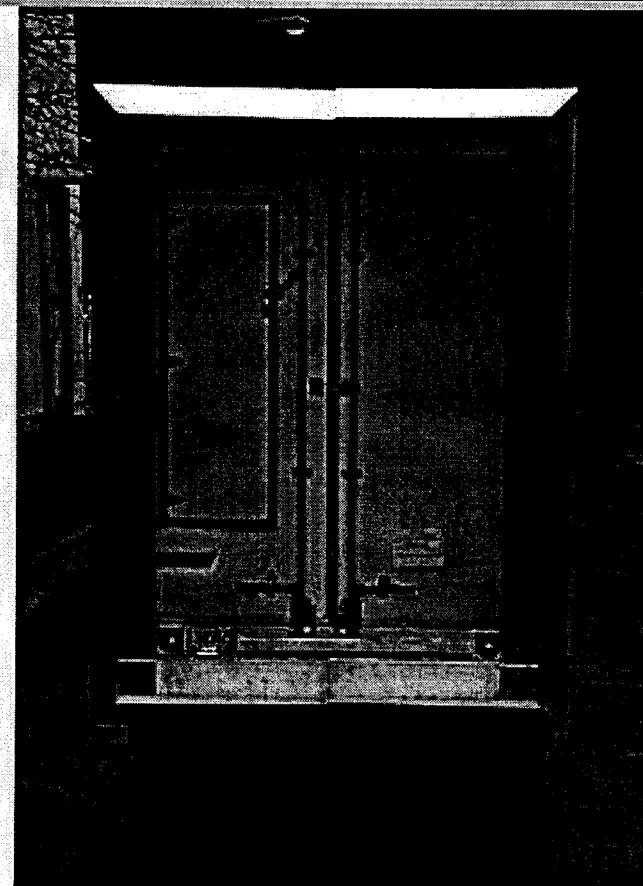


Deutz 20 hp Diesels (2)
To Drive Blowers

Rear View of Assembled Trailing-Edge Blowing System

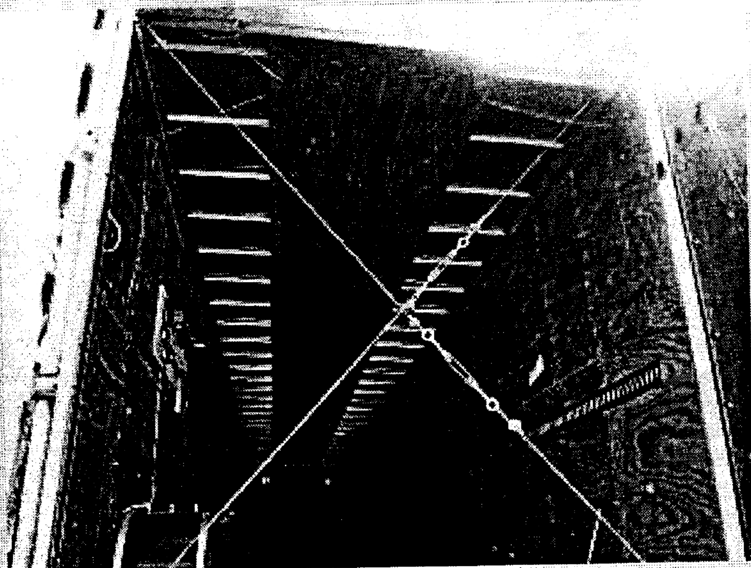


Doors Open in GTRI High Bay, Showing Blown Trailing Edges & Personnel Door

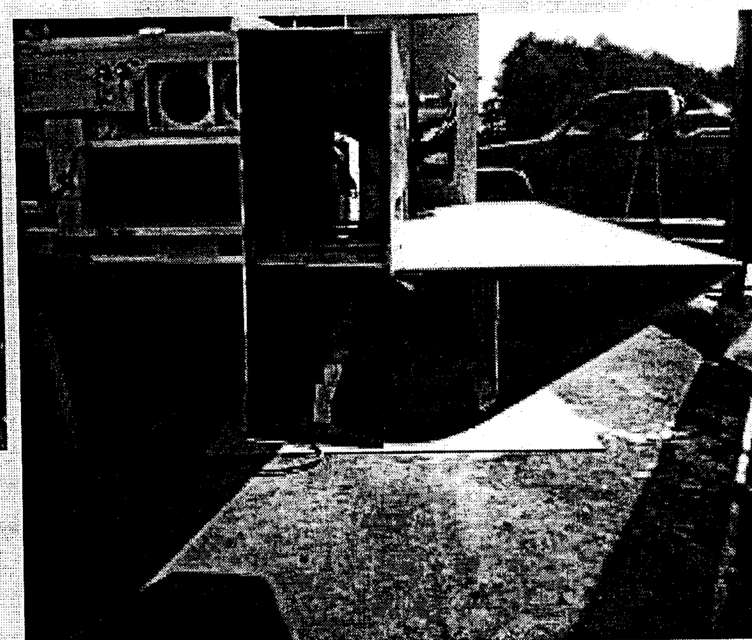


Doors Closed, PHV Approaching Final Assembly Area at GTRI

Internal Wiring, Structure and Instrumentation

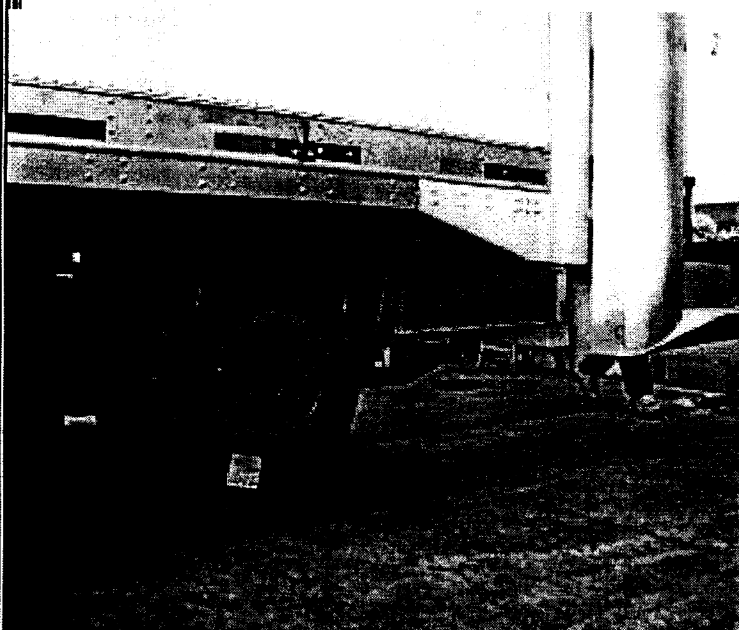


X-wire Bracing, Nat'l Instr. Pressure/Temp Instrumentation , and Data Transmission



Diffuser, Plenum, Duct, Slot, Slot Adjusters, 30° Turning Surface

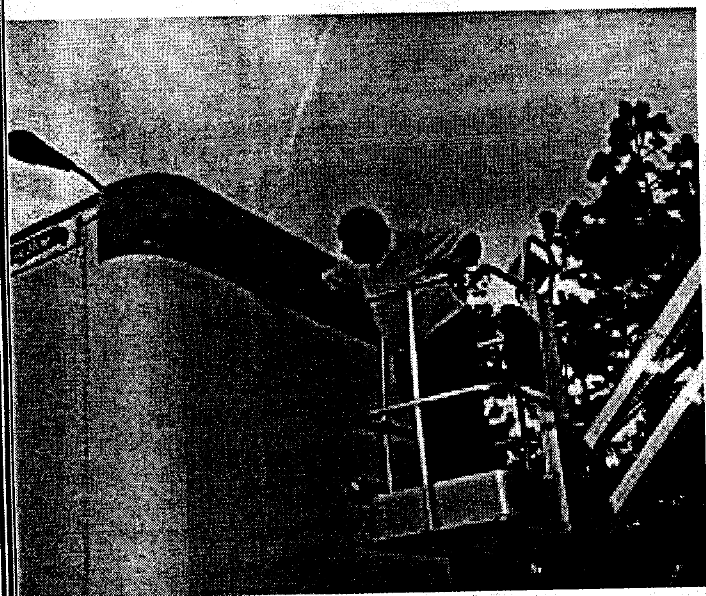
Static Testing of Trailing Edge Blowing System



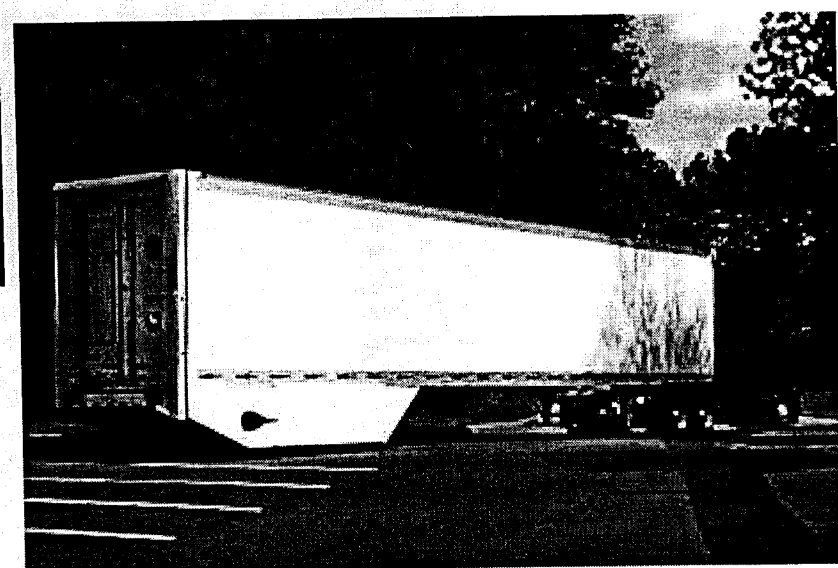
Blower, Screen, Diffuser &
Left Turning Surface (open)

Tuft Showing Flow Exiting the Diffuser
and Entering into Right Plenum

Final Assembly at GTRI and Departure to N.C.

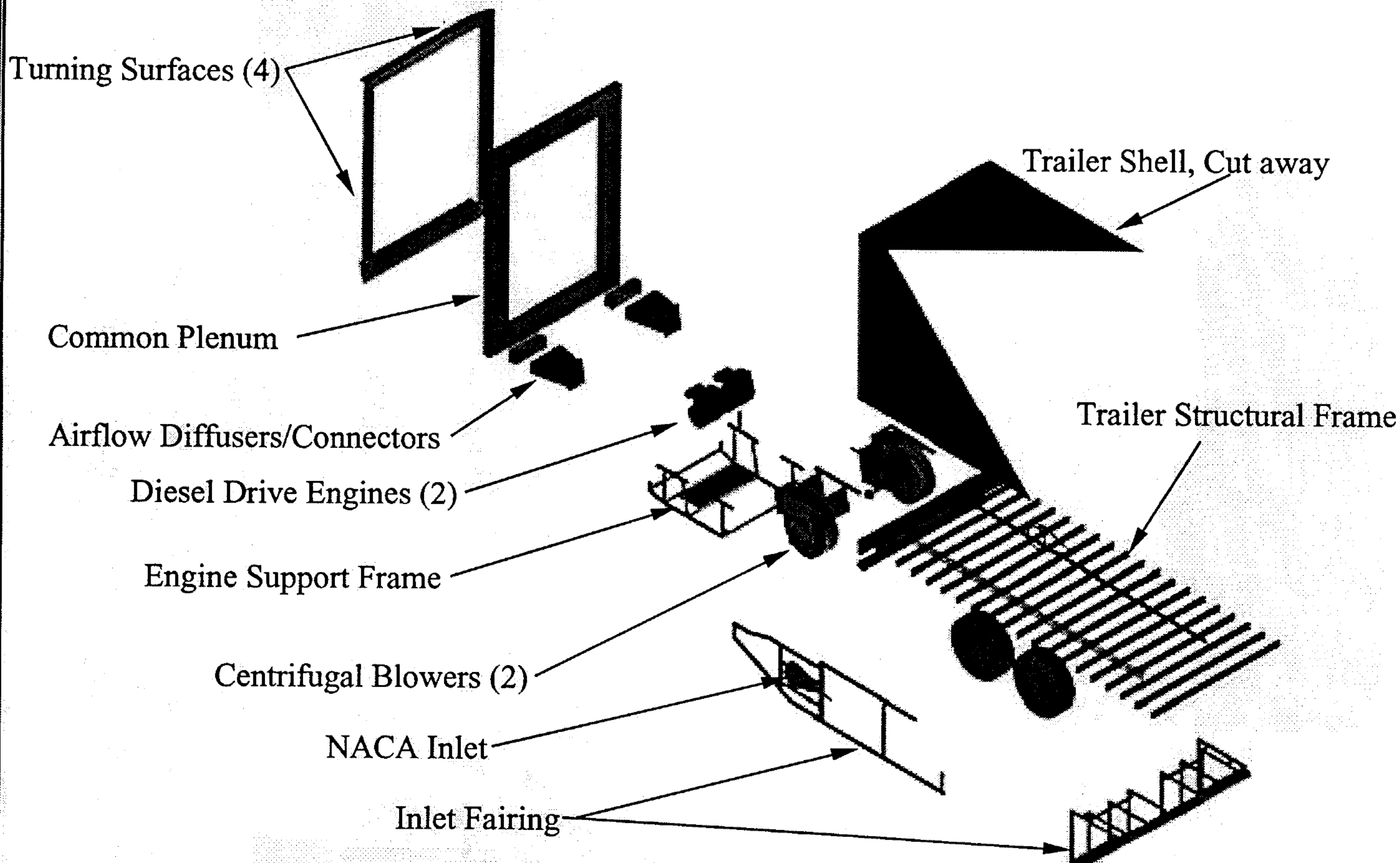


Installing "Radome"= LE Fairing
and Data Telemetry Antenna Cover



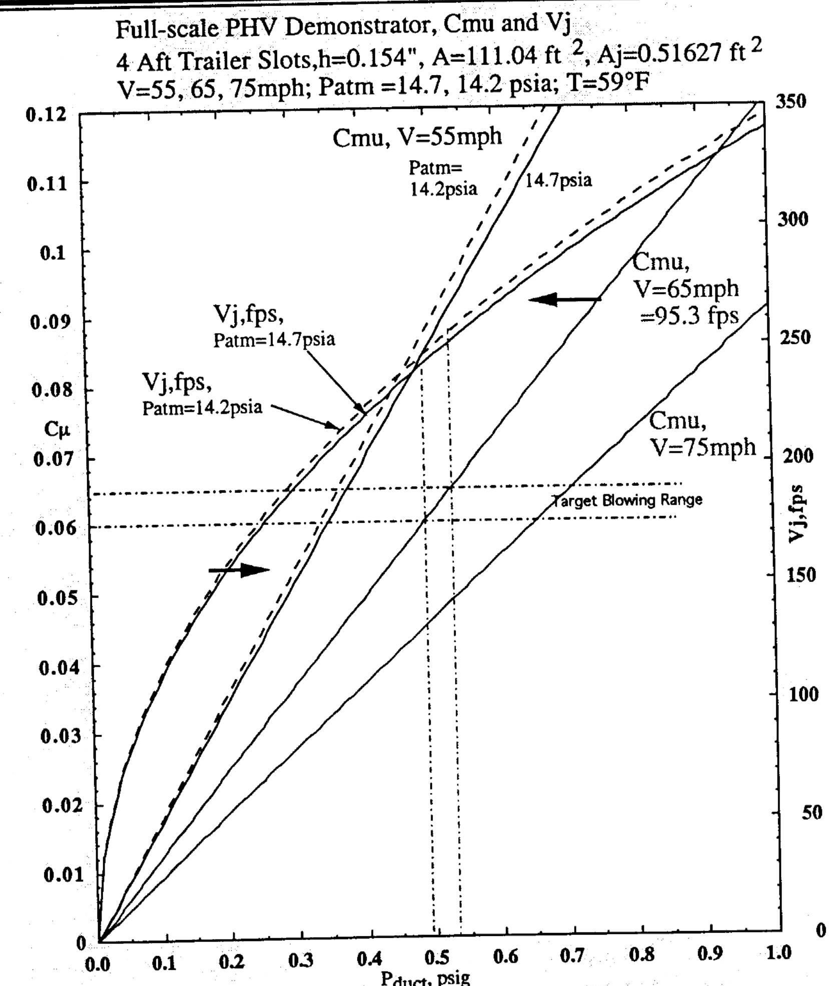
Departure from GTRI to Volvo;
Trailing Edge Still Unsealed

PHV Trailer Modifications for Blowing Systems

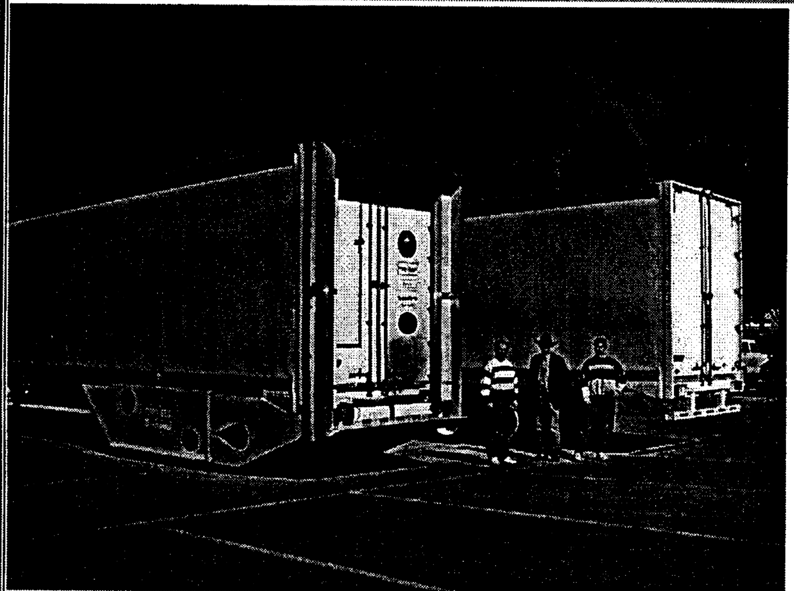


Designed & Modified by Prototype Shop Novatek, Inc

Blowing Design Parameters

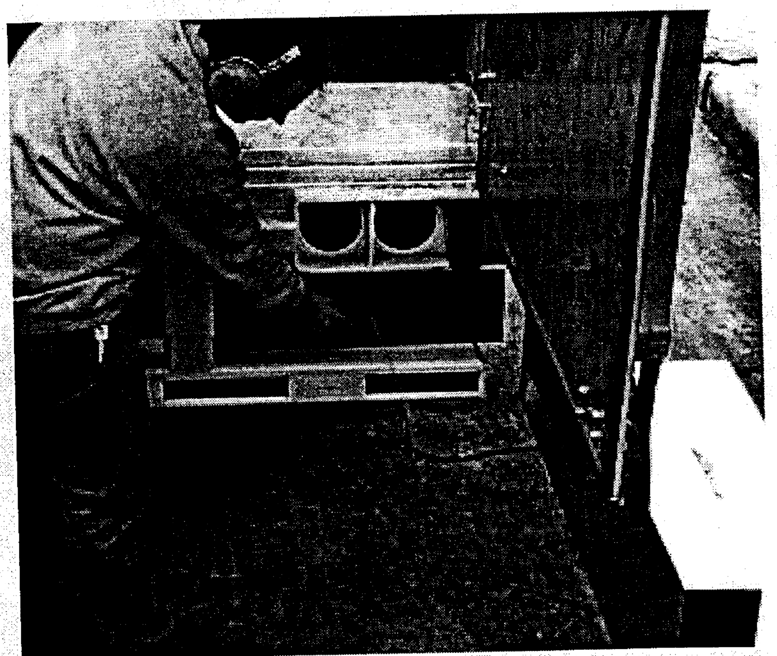


Pneumatic Heavy Vehicle Trailer Compared to Baseline Reference Trailer from Great Dane



Test PHV Features:
- 4 jet turning surfaces with plenums and blowing slots
- NACA inlet to entrain free-stream total pressure into blowers
- Diesel-driven external blowers feeding diffusers to plenums to slots
- Volvo engine fuel system, GTRI data telemetry of blowing parameters

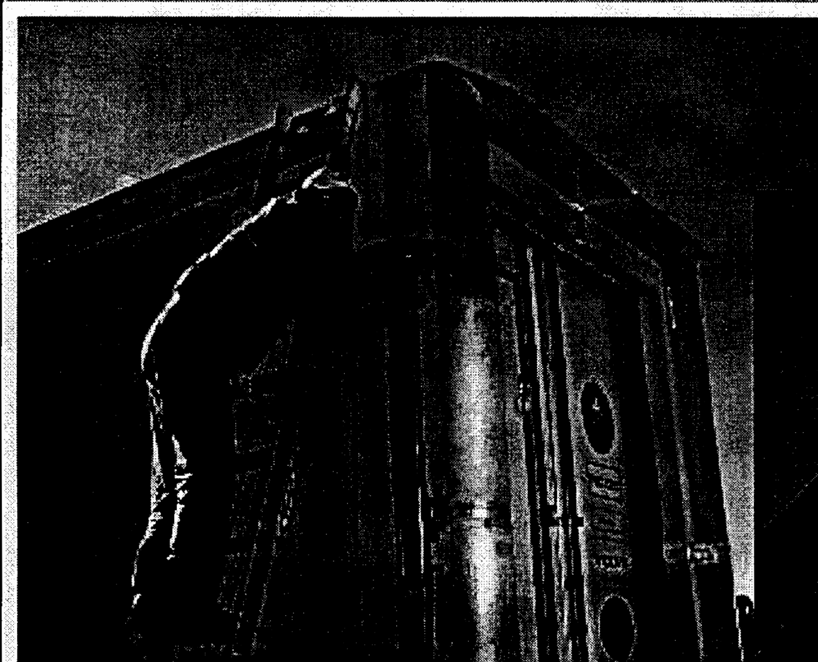
Flow Visualization of Blowing Jets



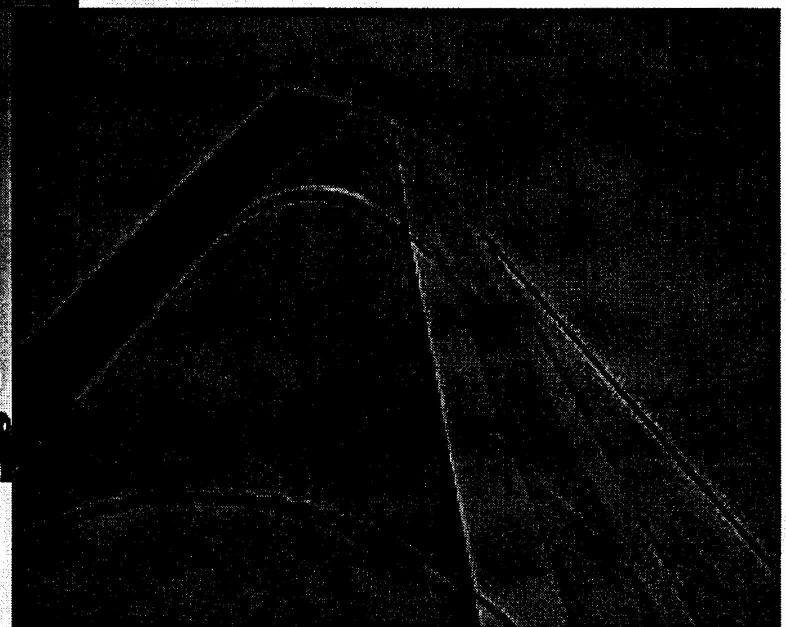
Tuft Showing Flow Uniformity at Diffuser Center

Combined Jet Strength and
Wake Contraction (see Shirt)

Static Jet Turning Displayed During Run-up Testing



Setting Slot Heights and Confirming Jet Turning at Low Blowing Rate



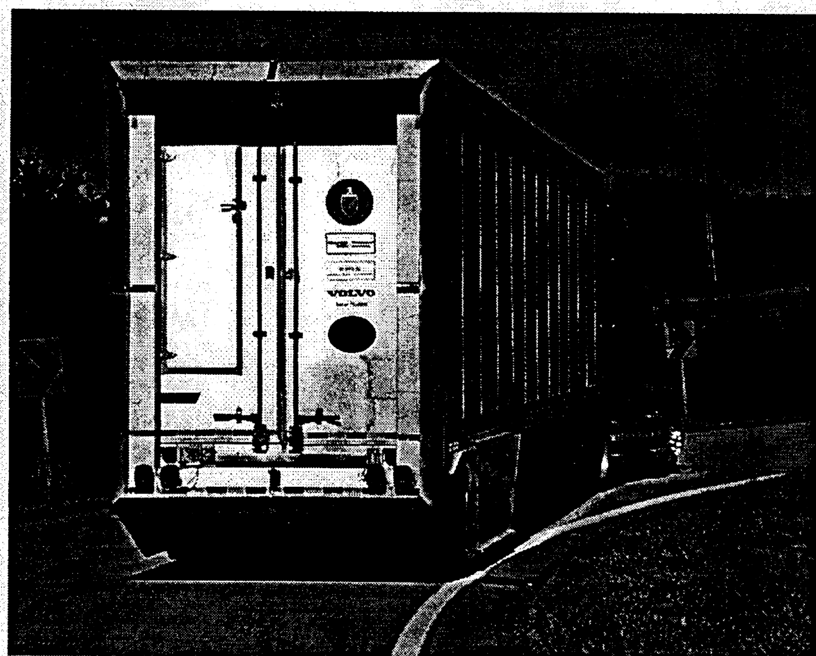
Right Rear Corner, looking up--
Tufts Show Jet Turning to Left:
90° on Side and 30° on Top

First Tuning Test Conducted at Volvo Trucks of North America, February 28-March 1, 2002

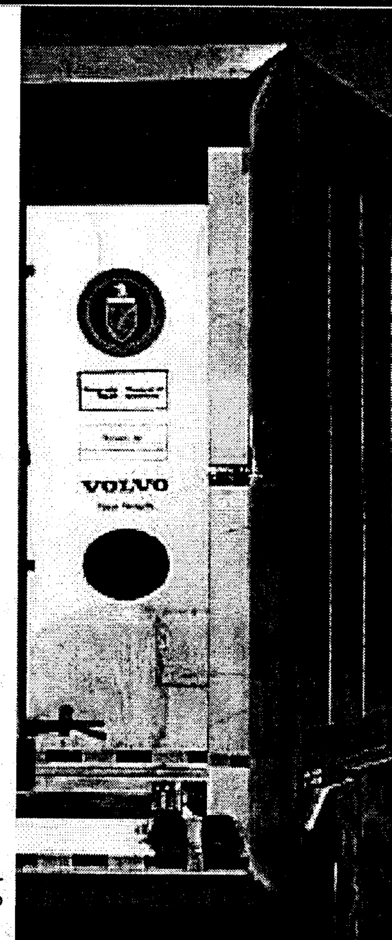
Objectives: • Blowing Optimization for Upcoming Fuel-Economy Test at TRC
• Instrumentation, Blowing, Data Reduction, & Control Systems Checkout

Conducted by : GTRI, Novatek, Volvo

On-the-Road Operation:Jet Turning Entraining the Flowfield and Reducing Vehicle Drag

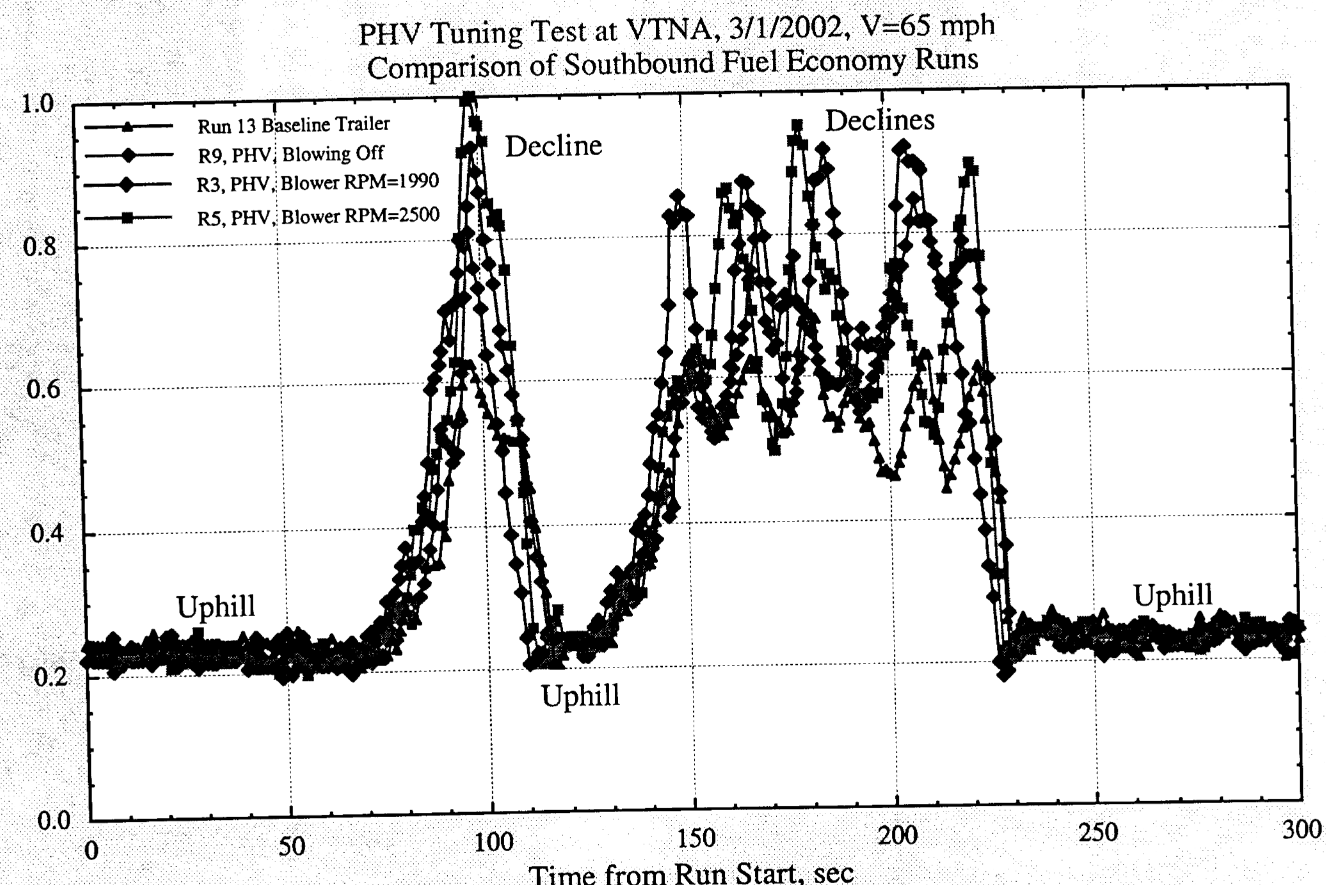


Rear View with Jets Blowing



Close-up of Tufts Showing Jet Turning

Tuning Test Preliminary Results, Southbound MPG



Typical Fuel Consumption Recorded during Blown, Unblown, and Baseline Test Runs at 65 mpg

Tuning Test Preliminary Results (V=65 mph), Changes in Time-Averaged Fuel Economy, %MPG

Configuration	Test Runs	Blower RPM	Route Direction	%MPG change	%Config'n MPG change
Baseline Trailer	13	0	Southbound	0.00	0
	14	"	Northbound	"	
PHV, No Blowing	9	0	SB	11.37	8.39
	10	"	NB	6.04	
PHV, Moderate C_μ	3	1980-2000	SB	10.80	9.36
	4	"	NB	8.22	
PHV, Higher C_μ	5	2500	SB	15.30	14.25
	6	"	NB	13.41	

Tuning Test Preliminary Results (V=65 mph), Comparison to GTRI Wind Tunnel Results, and Conclusions

Configuration	WindTunnel C_D	% C_D Change	% Equiv. GPM Reduction	Road Test Run No.	% GPM Reduction	% Equiv. C_D Change	% MPG Increase
Baseline, No Gap, Sq. LE & TE	0.627	0	0.0	13 (Gap)	0.00	0.00	0
Unblown PHV, Cmu=0	0.57	-9.1	-4.6	9	-10.21	-20.42	11.37
PHV,4 Slots Cmu=0.05	0.44	-29.8	-14.9	5	-13.27	-26.54	15.30

CONCLUSIONS:

- Limited Tuning Runs confirmed up to **15.3% increase in MPG,** or about **26.5% reduction in C_D**, due to blown PHV configuration, **but** this first Tuning Test **was not optimized** (Speed, Temps, Blowing rate, etc.)
- Plans to conduct 2nd Tuning Test (TT2) with suggested test procedure and vehicle improvements prior to SAE fuel economy test at TRC

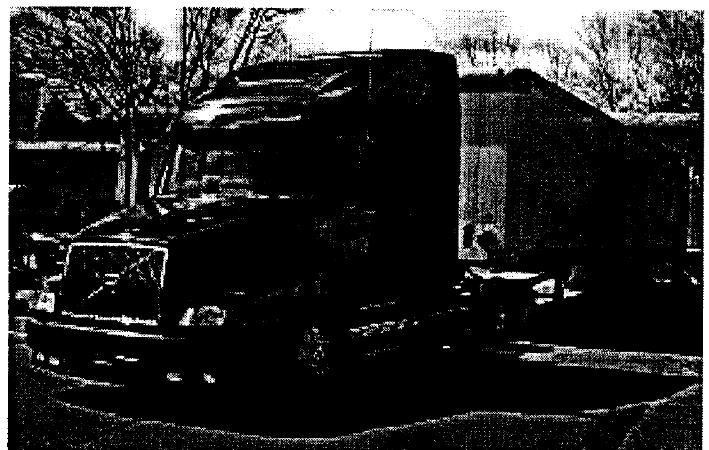
Initial Tuning Test Problems -- Correct for TT2

Corrections to be made:

- Right Diesel stopped (errors in some blowing data); Repair engine
- Change gearing on diesel-to-blower connections
- Bottom and front engine fairings were omitted: Install these
- No fuel flow meters for blower diesels; Install these
- Free stream pitot-static probe in side wall boundary layer; re-locate

Improvements to be made:

- Run at higher speed for more Aerodynamic Dominance (75 vs 65 mph)
- Run on warmer day with some sidewinds and gusts
- Reduce blowing slot height for higher Vj
- Run with less effectively faired tractor



Upcoming SAE Type 2 Fuel Economy Tests on PHV

- At Transportation Research Center (TRC), East Liberty, OH: Summer ,2002
- 1 PHV Test Truck & 1 Control HV, running simultaneously on 8-mile track
- Both HVs Loaded to Typical Operating Weight (~60,000 lb.)

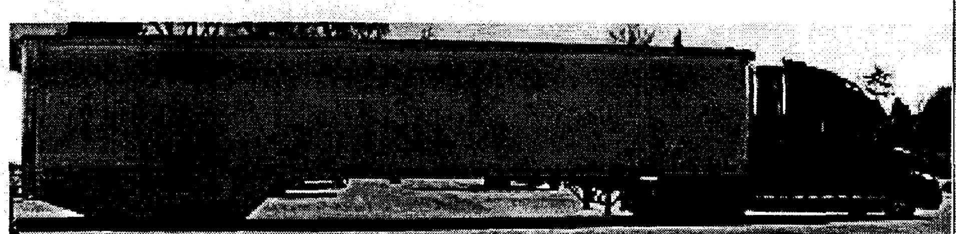
- Test Configurations for PHV (each run = 3 speeds, 2-3 days; 450 miles):
  1. Blowing **On** , **Cμ = best**
     1.a, 1.b: Two Optional Blowing-on Runs: **Intermediate Cμ's**
  2. Blowing **Off**, **Cμ = 0**
  3. Blowing **Off,** Round Leading-Edge and Trailing-Edge Aero **Surfaces Off**
  4. Blowing **Off,** Engine, Blower & Fairing Components Off = **Baseline Trailer**
  5. Mirrors **Off**, for DOT

- **Results:** For each Configuration: Fuel Burned / Miles Driven, corrected by Control HV

CONCLUSIONS:Pneumatic Aerodynamic Concepts Now Verified ~Offer Significant Potential For Improvement of Heavy Vehicles; (Green = Confirmed in Tuning Test 1)

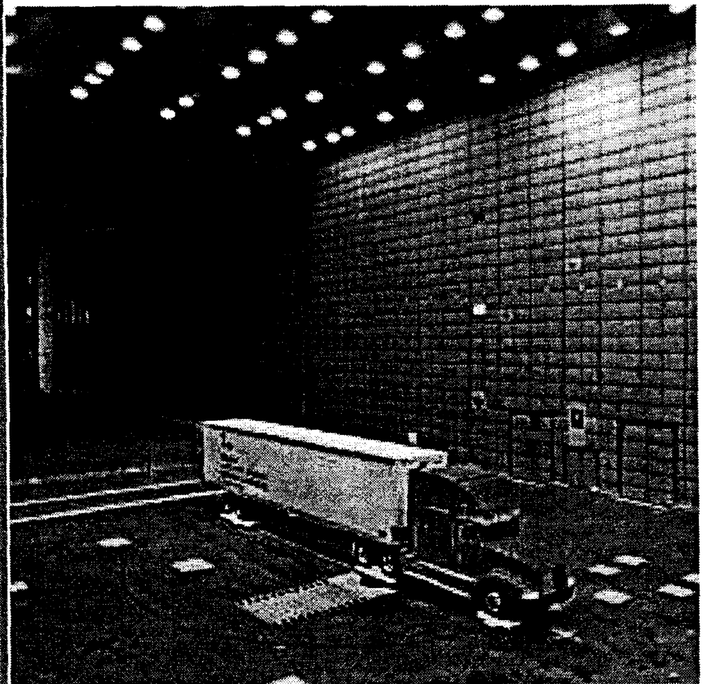
- Pneumatic Devices on trailer, **blowing slots on all sides and/or front top**
- **Separation control & base pressure recovery, LE suction = drag reduction; or Base suction = drag increase   Latest test results: Blowing-on ΔC_D = -26% or more**
- Additional lift for **rolling resistance reduction** ($F_{Rolling} = \mu N$, where N=Wt - Lift), **or** Reduced lift (increased download) for **traction and braking**: instantaneously **switchable**
- Partial top/bottom slot blowing for **roll control & lateral stability**
- One-side blowing **(LE or TE)** for **yaw control & directional stability**
- **Aerodynamic control** of all three forces and all three moments
- **No moving parts**, small component drag; **Very short aft addition=no length limitation**
- **Splash, Spray & Turbulence** Reduction; Reduced **Hydroplaning**
- Use of **existing** on-board compressed **air sources** (exhaust,turbocharger,brake tank,electric
- **Advanced Pneumatic Cooling Systems (Aerodynamic Heat Exchanger)**
- **Safety of Operation**
- **First On-Road Test Now Completed; MORE to Come!!**

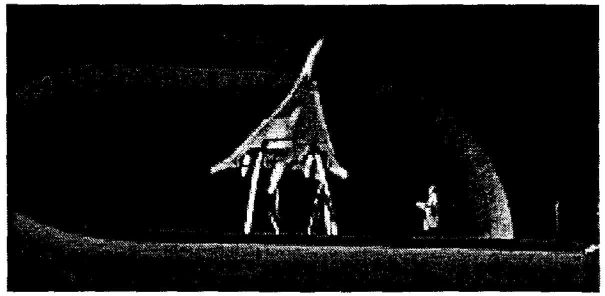
GTRI PATENTED CONCEPTS

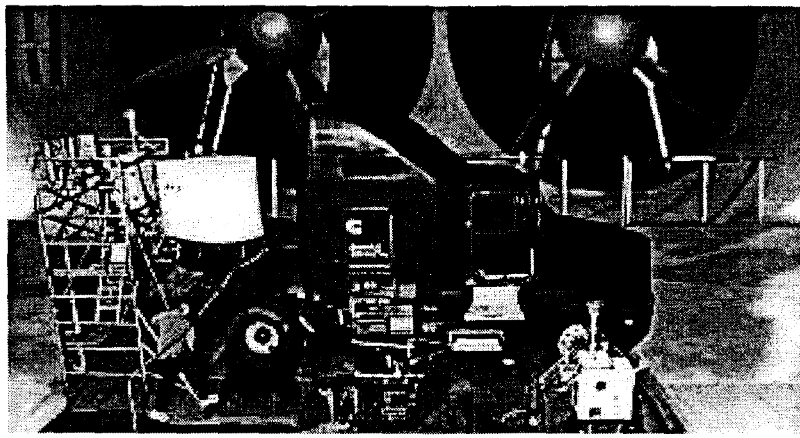


Follow-On Large-Scale Wind Tunnel Investigations

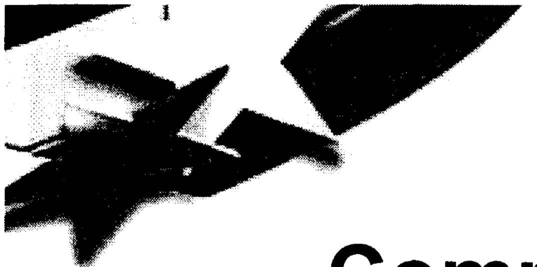
To Investigate: Full-Scale C_D alone; Lateral /Directional Stability; Side Winds (Yaw); Safety of Operation; Full-Scale Reynolds Number







NASA Ames Full Scale Complex 80' x 120', V=115 mph ..Or.. ODU Langley Full Scale Tunnel, 30' x 60', V=80-120 mph



Computational Prediction for a Simplified Truck Geometry

Walter H. Rutledge

Mary McWherter-Payne, Chris Roy,

Dave Kuntz and Jeff Payne

Aerosciences and Compressible Fluid Mechanics Department

Sandia National Laboratories

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

Lawrence Livermore National Laboratory

April 3rd and 4th, 2002

Outline

- Introduction – SNL Role
- FY02 Tasks and Budget
  - Status
  - Results from 2D GTS grid studies
  - New 3D GTS grid
- Additional Tasks (unfunded)
  - Dissection of 10 Degree Yaw GTS Solution
  - GCM
    - 2D
    - 3D
- Leveraging (additional money, ESRF)
- Conclusions

Introduction

- Overall SNL Role: To provide technical insight to industry relative to:
  - the role of current and future (advanced) computational methods for truck/trailer aerodynamic design
  - Aerodynamic drag reduction for truck/trailer systems
- At end of FY00, SNL moved from just RANS to hybrid RANS/LES
- FY02:
  - The focus is on better y+ resolution for turbulence modeling (New 2D and 3D grids)
  - New SNL participants (Chris Roy, Dave Kuntz, Jeff Payne) in addition to Mary McWherter-Payne

Sandia Computational Approach

Steady RANS

- Spalart-Allmaras
- k-epsilon
- k-omega Wilcox

Unsteady RANS

- Spalart-Allmaras
- k-omega Wilcox
- Durbin's v^2f

Hybrid RANS/LES

- Detached Eddy Simulation
- Hybrid RANS/LES

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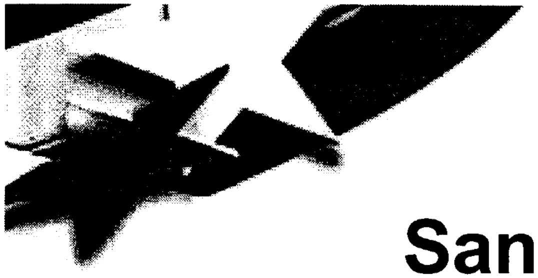
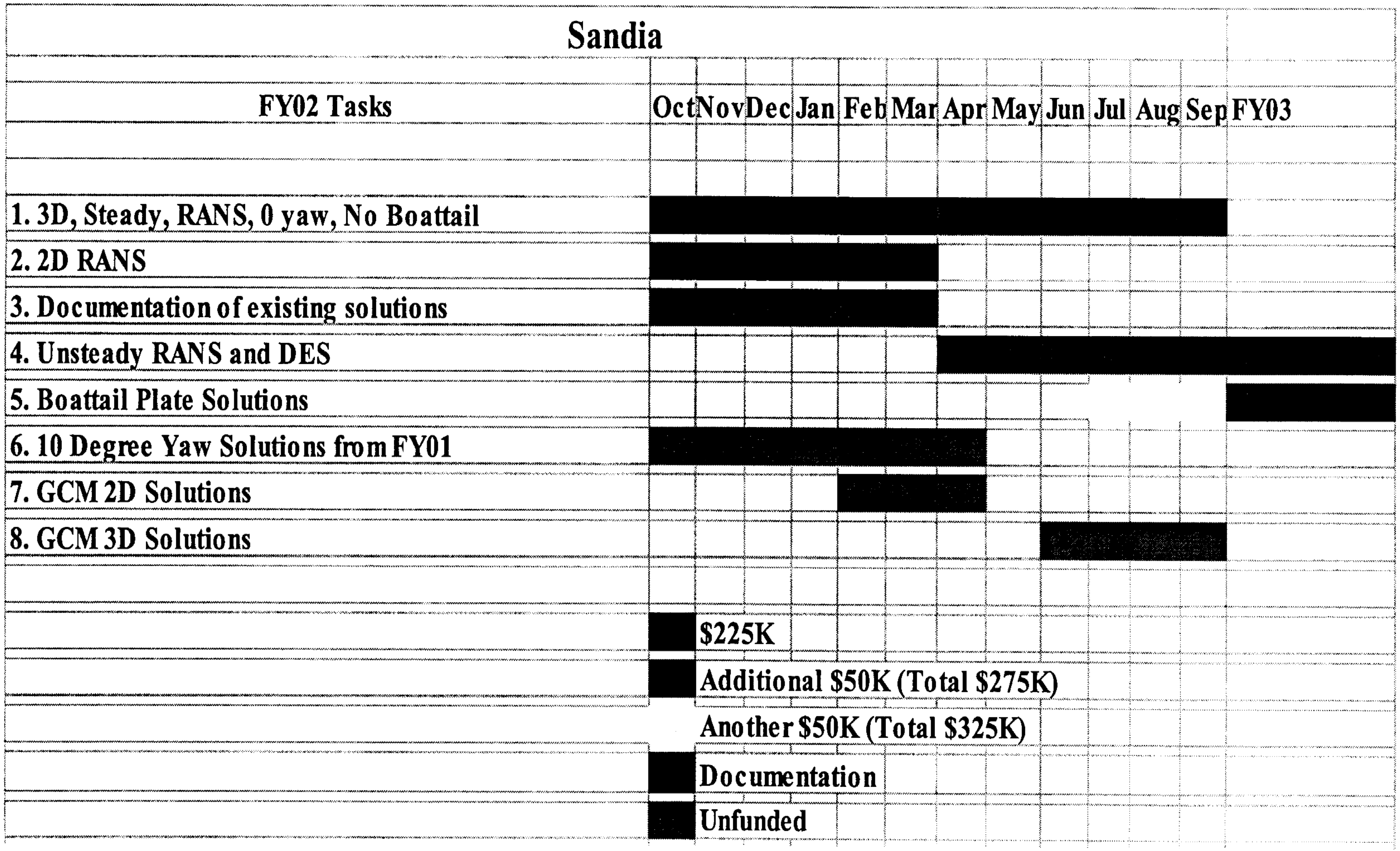


Sandia FY02 Tasks and Budget



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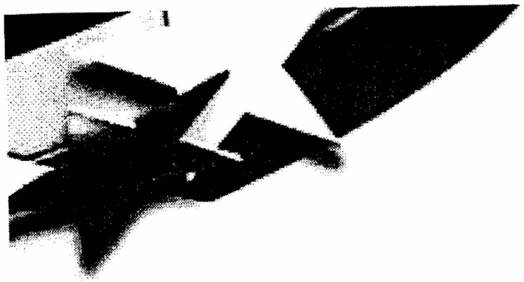

Status of FY02 Tasks

- Task 2: GTS, 2D, RANS Documentation in progress
  - y+ grid studies completed
  - 2D solutions completed for three turbulence models
- Task 1: GTS, 3D, Steady RANS
  - New 3D mesh completed
    - Coarse (300,000 cells)
    - Medium (2.5 million cells)
    - Fine (20 million cells)
  - Grid needs to be decomposed for parallel processing
  - k-omega/Wilcox ready to run
  - Other models to be run (time/funds permitting)
    - Spalart-Allmaras, k-epsilon

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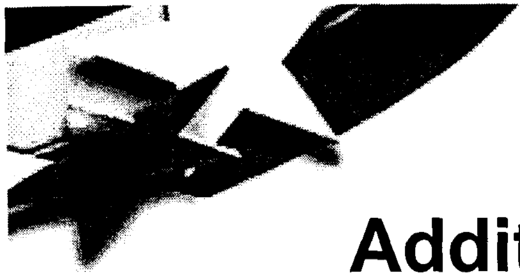
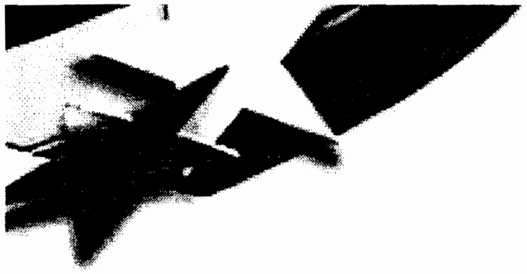
Status of FY02 Tasks

- Task 3: Documentation of existing solutions
  - SNL memo submitted for review (April 2002)
  - Working with LLNL on documentation of previous SNL activities (through FY01)
    - Salari and McWherter-Payne
- Task 4: Unsteady RANS and DES no activity
- Task 5: Boattail with RANS: no activity



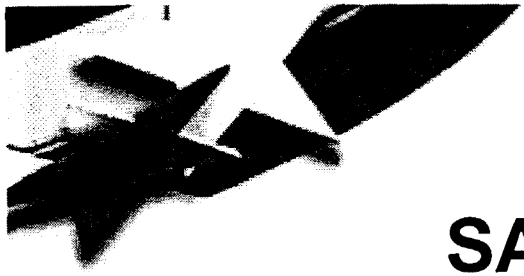
Additional FY02 Tasks (Unfunded)

- Task 6: GTS, 10 Degree Yaw (FY01 medium mesh, S-A)
  - Flow field plots
  - Comparisons with experiment
    - Drag
    - Skin friction
    - Pressure Coefficient
- Task 7: 2D, GCM
  - Generated multiple meshes
  - k-omega/Wilcox medium mesh solution obtained
  - Appropriate y+ values determined
- Task 8: 3D, GCM
  - Obtained NASA ProE file, but surfaces are missing



The Budget, The Team

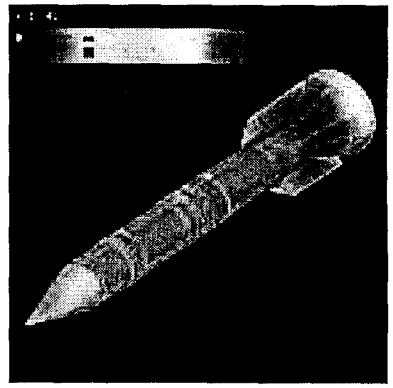
- The Budget: $225K ($50K less than anticipated)
- The Team:
  - Walt Rutledge (Manager)
  - Mary McWherter-Payne
  - Chris Roy
  - Dave Kuntz
  - Jeff Payne (consulting)

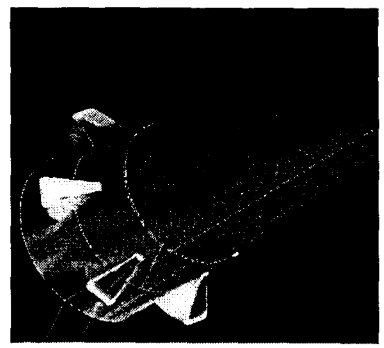


SACCARA Code Capabilities

Sandia Advanced Code for Compressible Aerothermodynamics Research and Analysis

- Multi-block, structured grids for 2-D, Axisymmetric, and 3-D flows
- Solution of the Full Navier-Stokes equations for compressible Flows
- Finite volume spatial discretization (steady and unsteady)
- MP implementation on a variety of distrubuted parallel architectures (IBM, Intel, etc.)
- Implicit time advancement schemes
- Subsonic $\rightarrow$ Hypersonic flows
- Zero-, one-, and two-equation turbulence models
- Ideal, equilibrium, and thermo-chemical nonequilibrium finite-rate gas chemistry
- Rotating coordinate system





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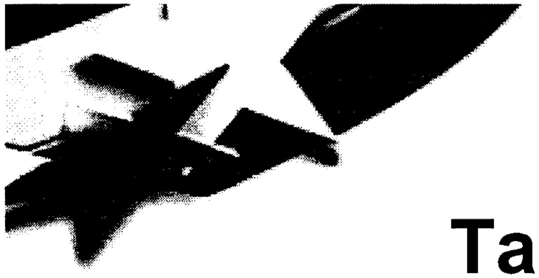
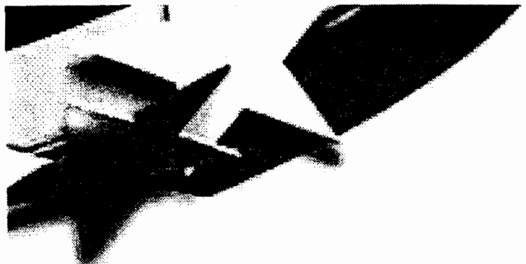


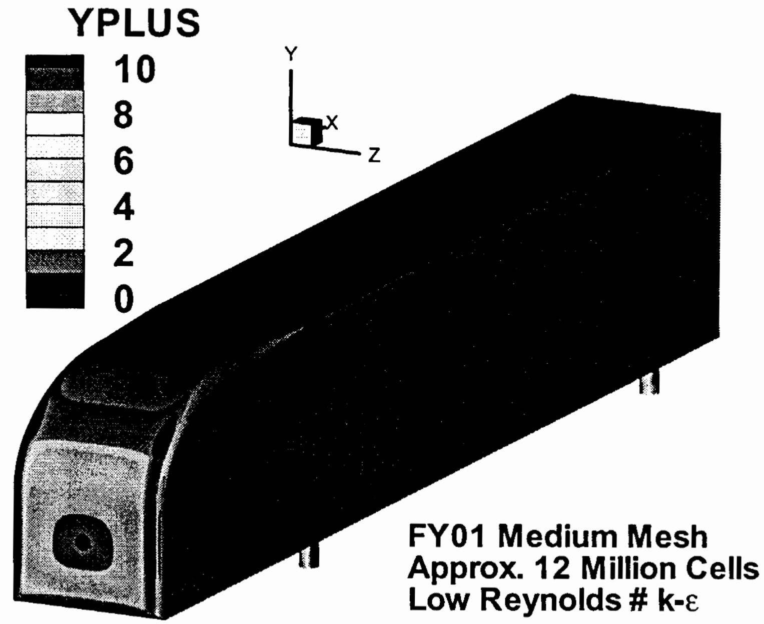
Task 2: GTS 2D Grid Studies

Want to understand strengths/weaknesses of RANS models

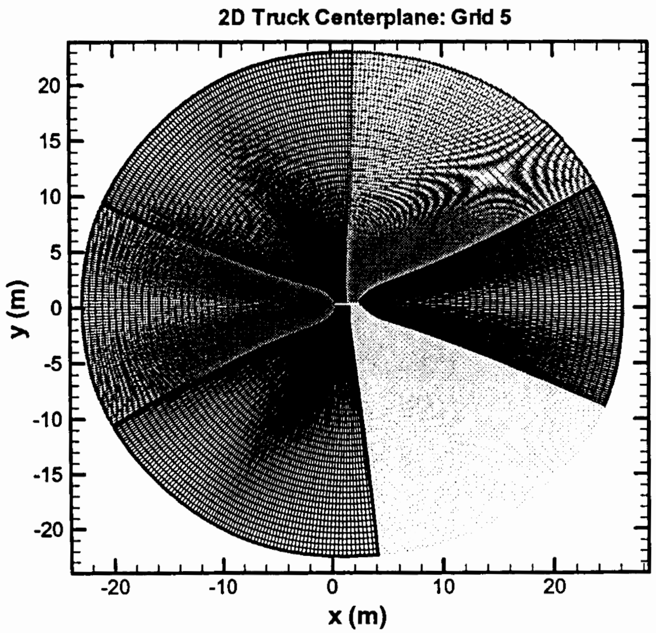
- Motivation: During FY01, it was determined that k-omega/Wilcox would not run on FY01 medium mesh (12 million cells)
  - suspected that wall y+ values were too large
- 5 new 2D meshes completed with max y+ of 0.5, 1, 2, 5, 10
- Ran k-omega/Wilcox, k-epsilon and Spalart-Allmaras on all five meshes to determine:
  - Required y+ to obtain solution
  - Effect of y+ on accuracy of solution

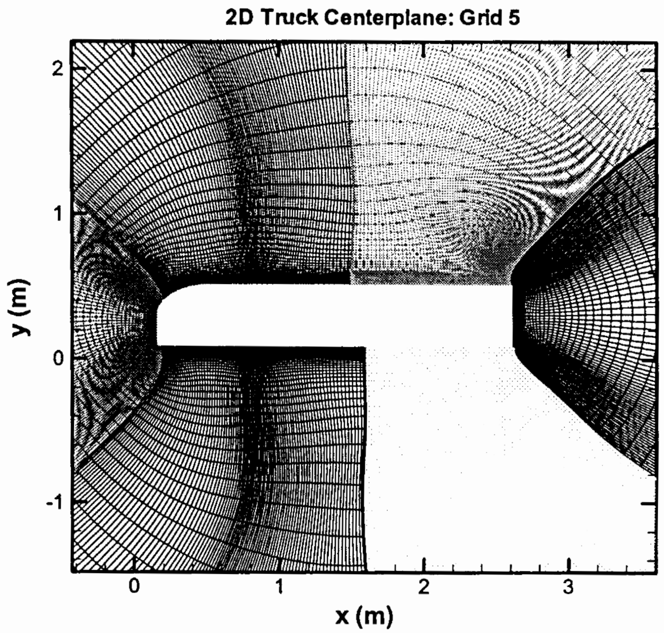


- Previous 3D mesh: y^+ too large
- New 2D meshes for y^+ study
  - hyperbolic meshes (no tunnel)
  - retain FY01 axial spacing
  - grid1: FY01 normal spacing
  - grid2 through grid5: refine in wall normal direction only



FY01 Medium Mesh
Approx. 12 Million Cells
Low Reynolds # k-ε





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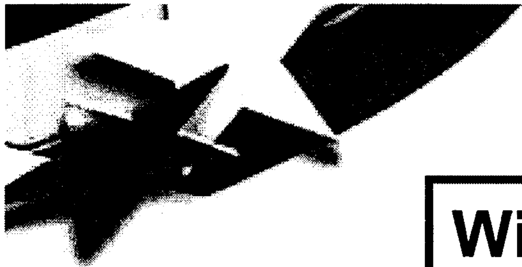
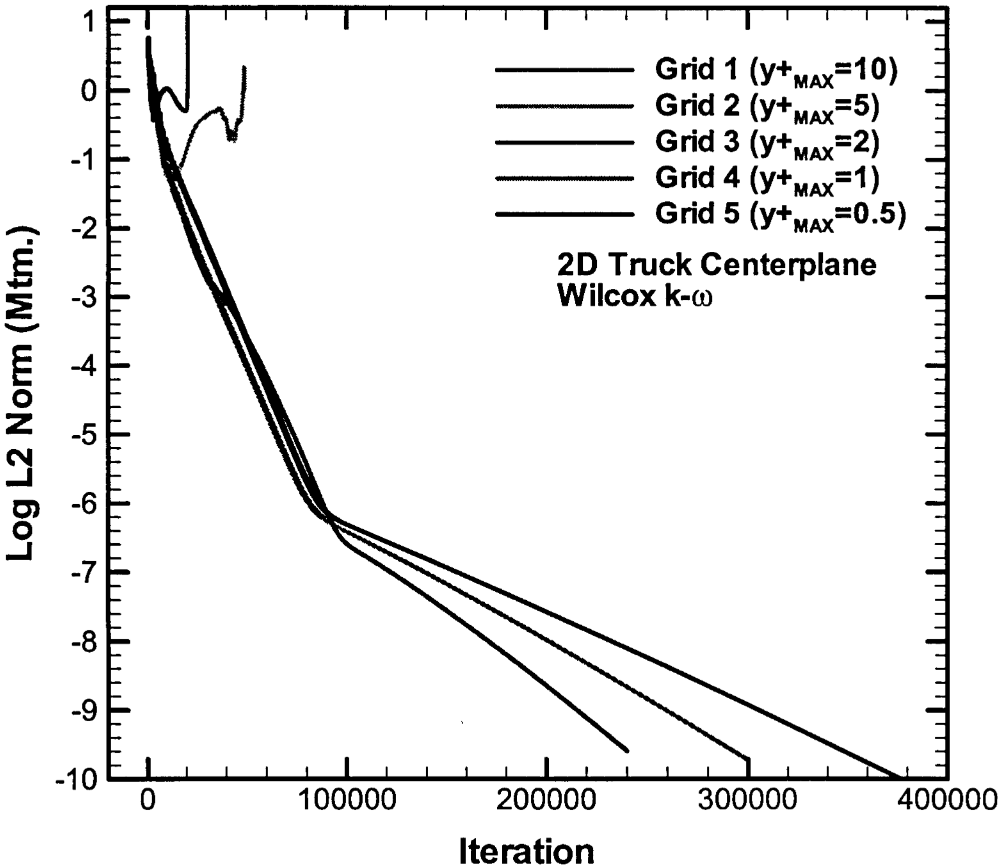
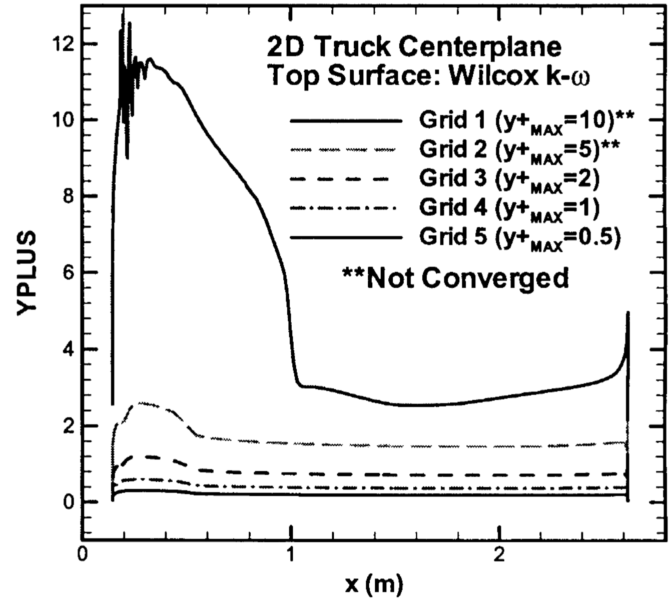
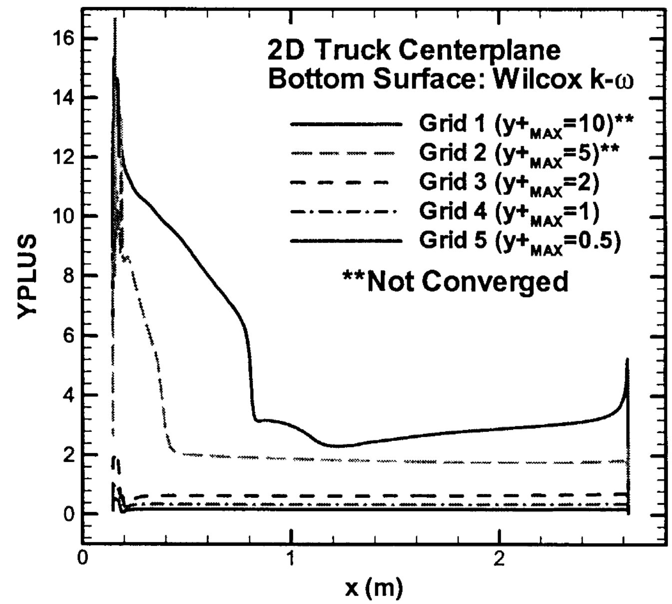


Wilcox (1998) k-ω



Convergence History





Wall y+ Values

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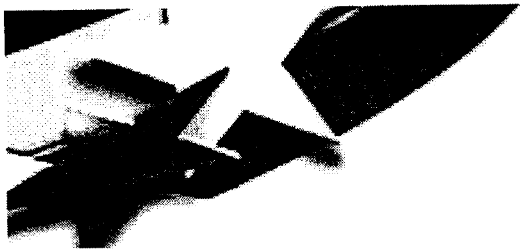
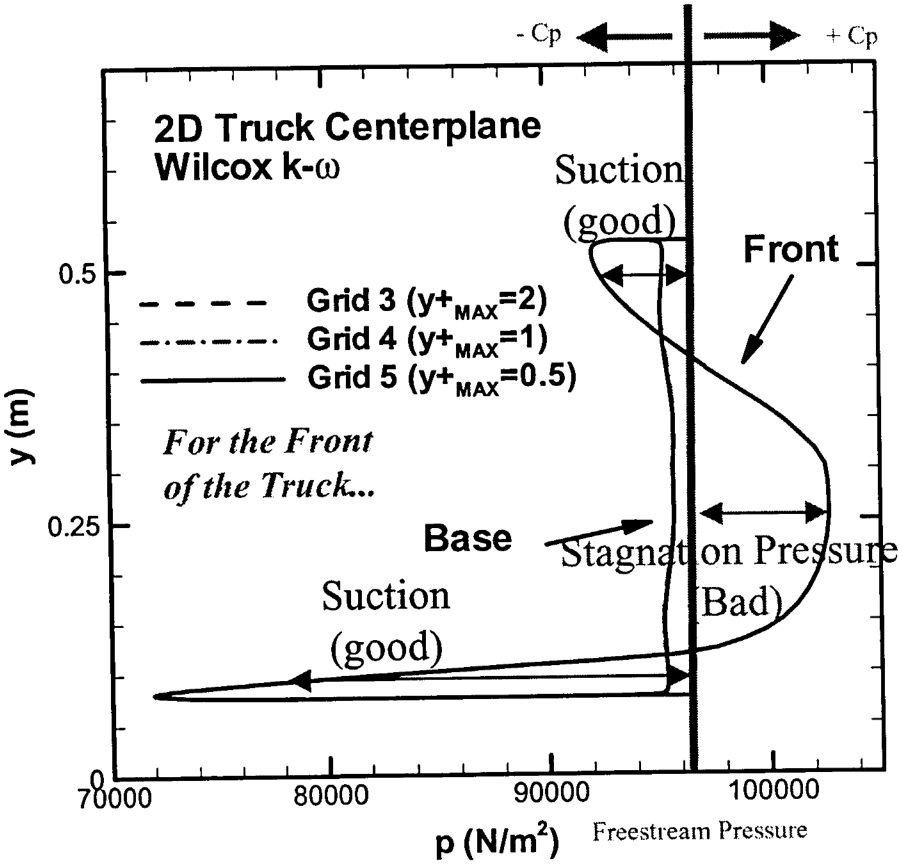
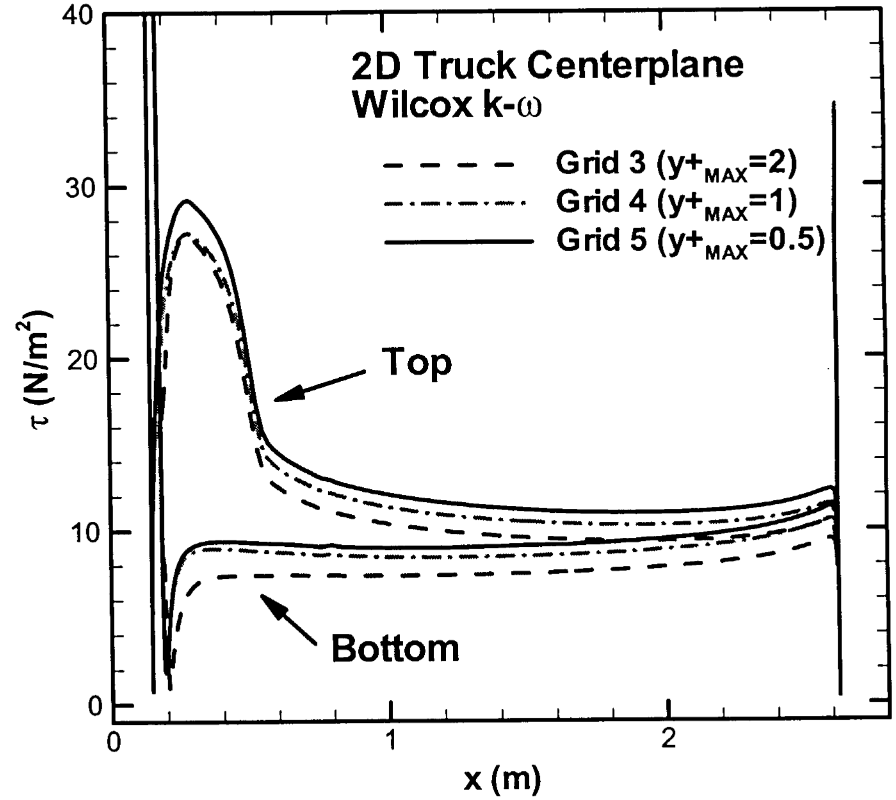


Wilcox (1998) k-ω



Surface Pressure



Shear Stress

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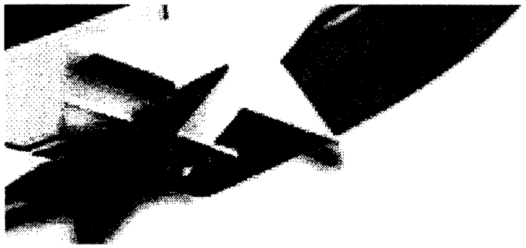
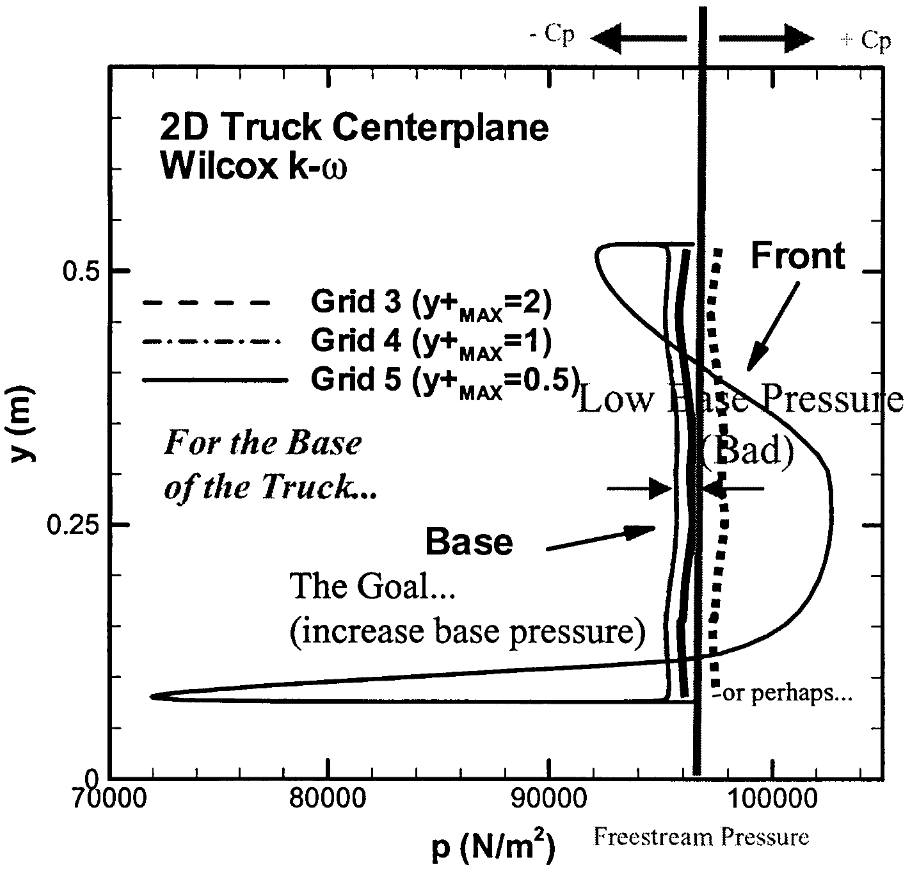
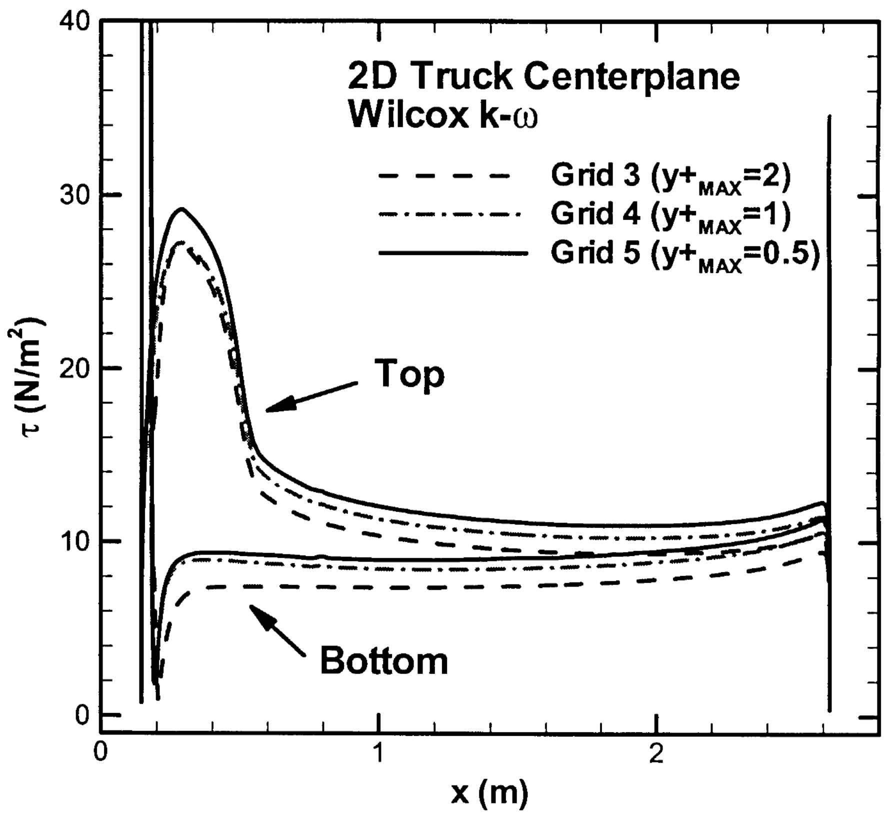


Wilcox (1998) k-ω



Surface Pressure



Shear Stress

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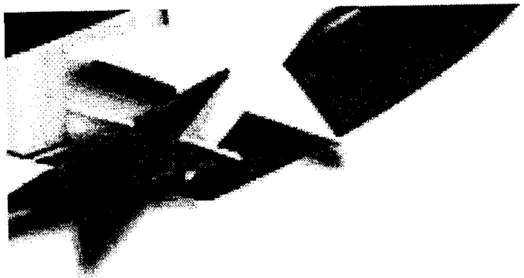
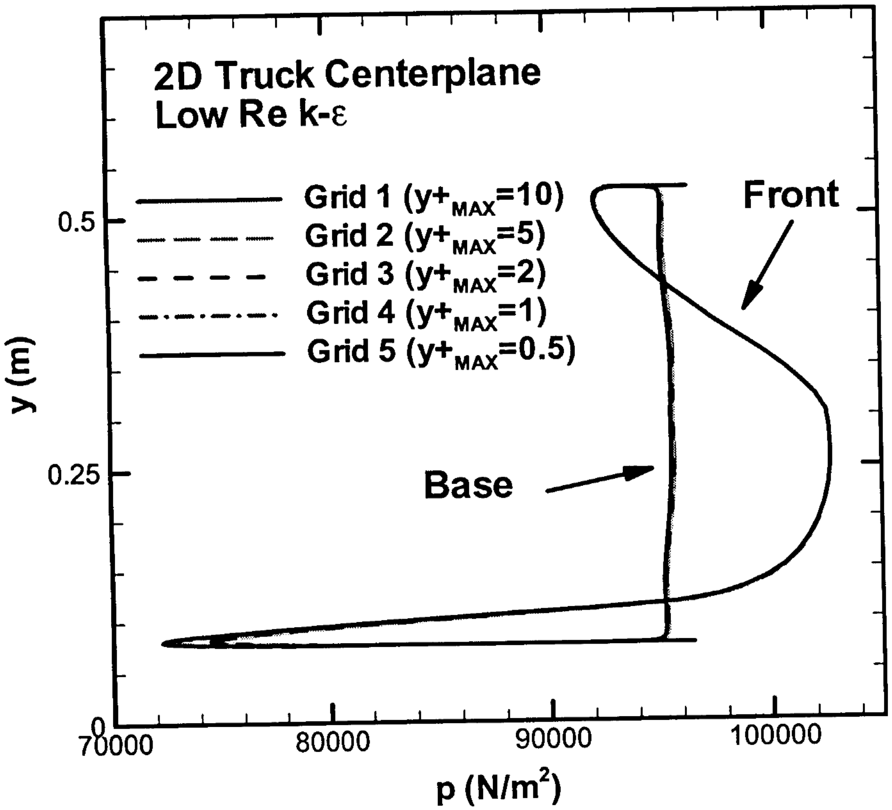
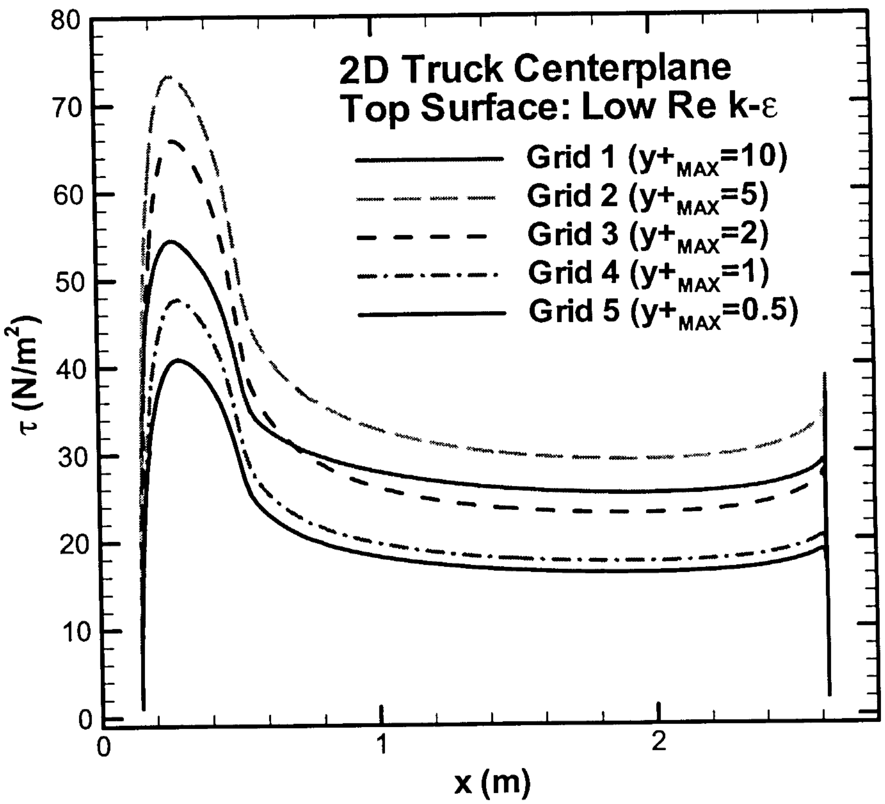


Low Reynolds Number k-ε



Surface Pressure



Shear Stress

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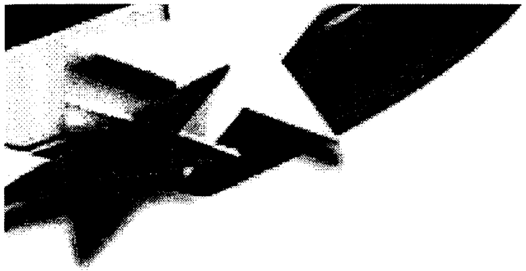
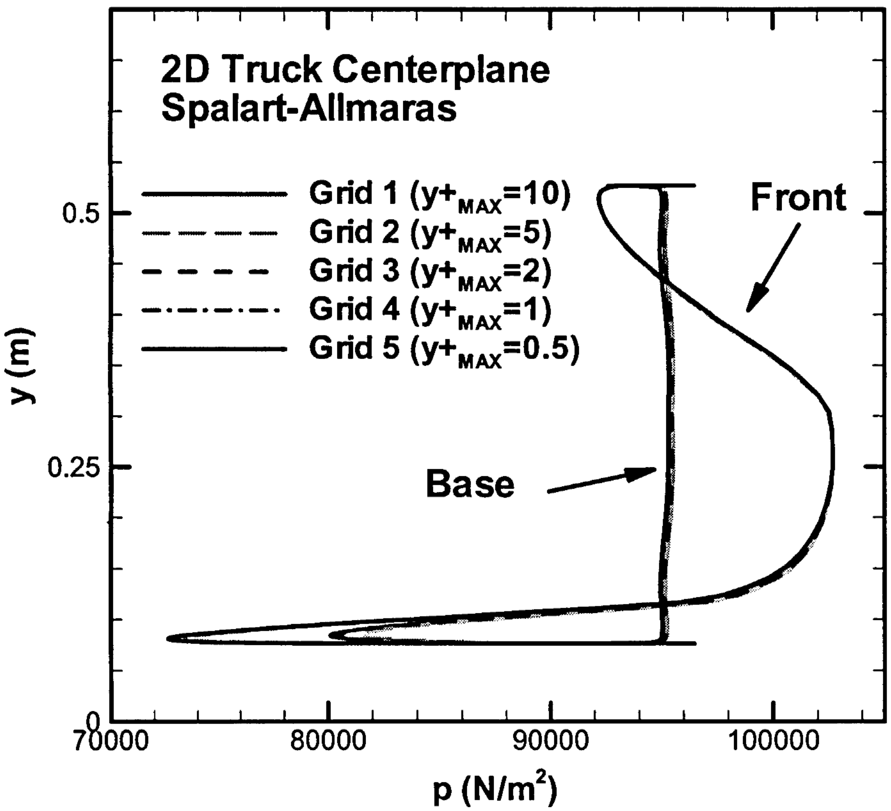
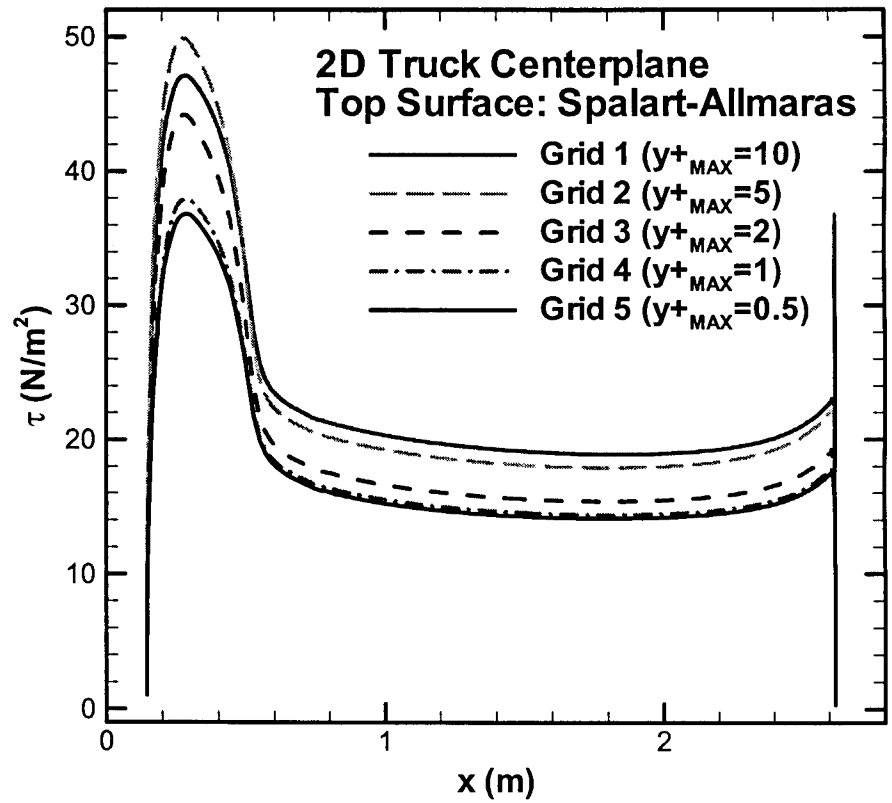


Spalart-Allmaras



Surface Pressure



Shear Stress

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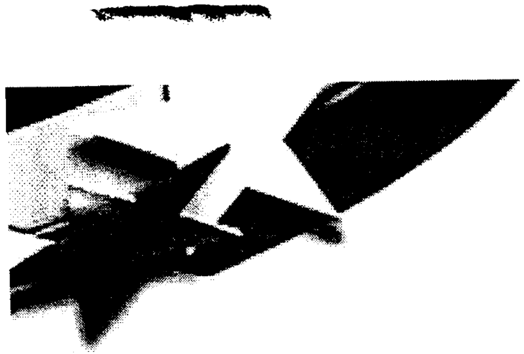
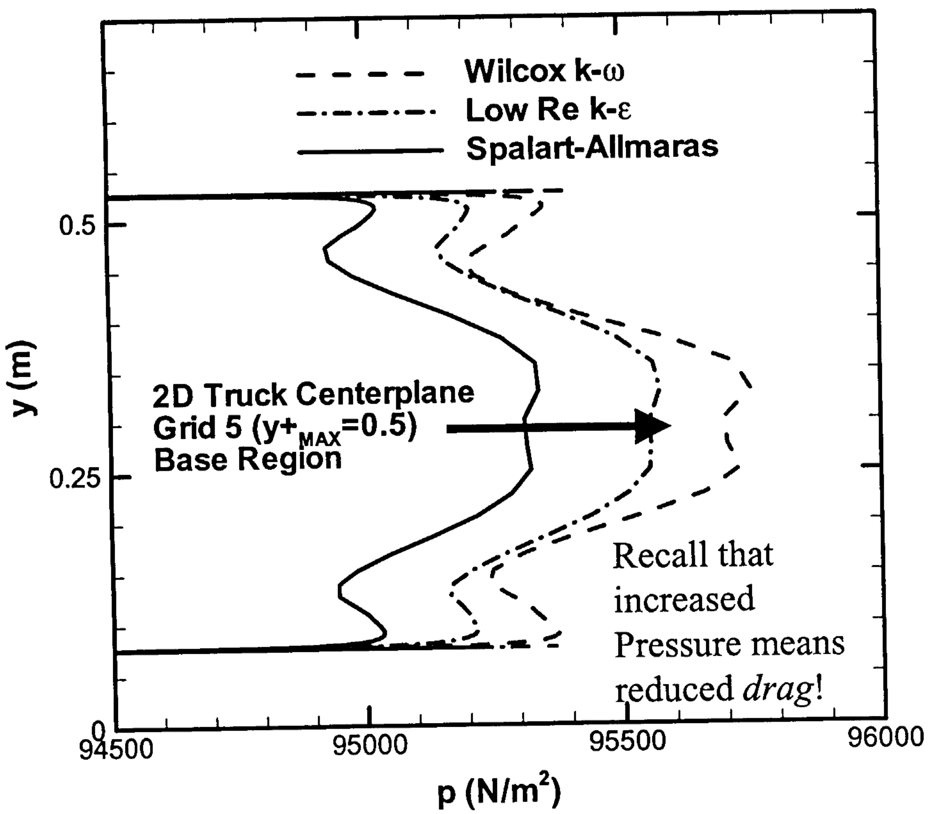
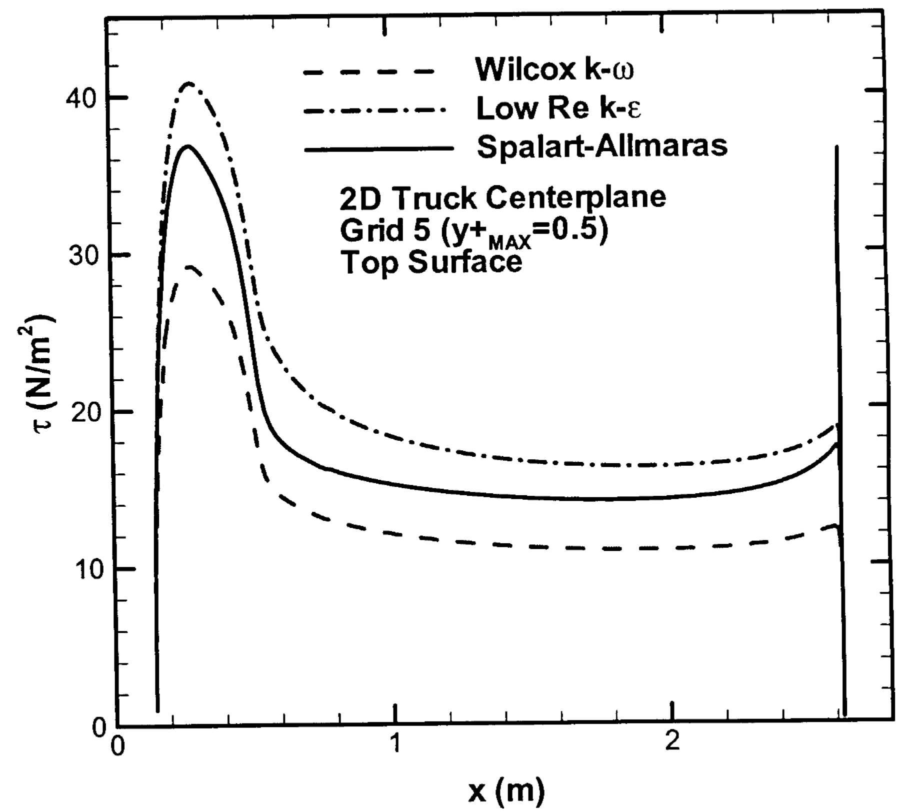


Model Comparison: Grid5



Surface Pressure



Shear Stress

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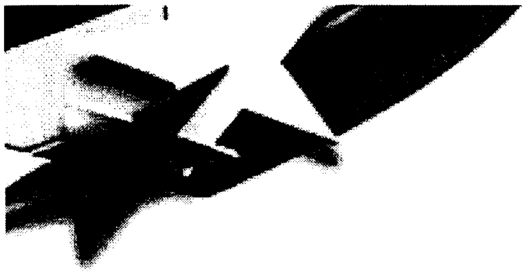
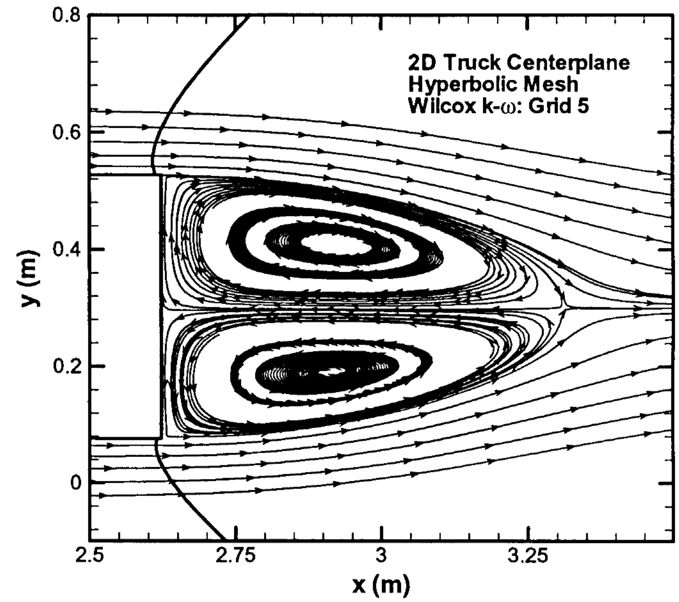
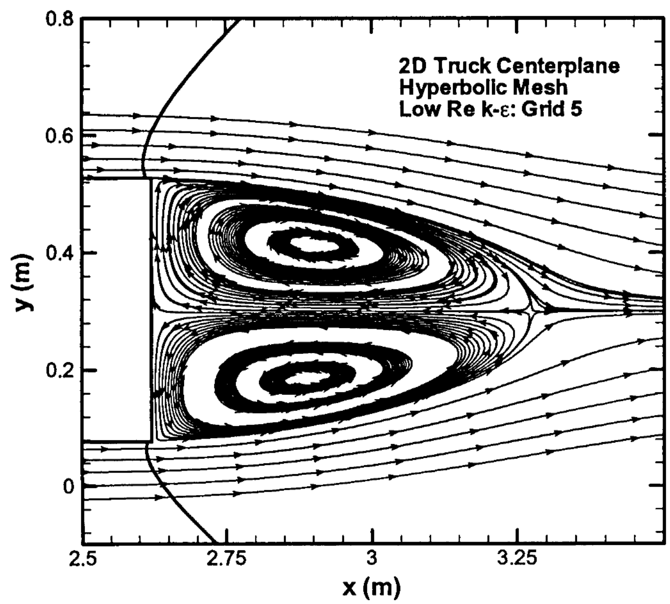
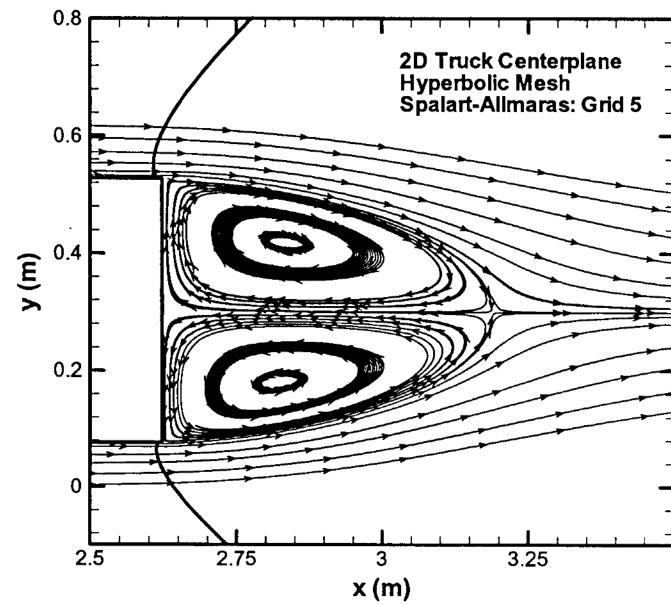


Model Comparison: Grid5

	Recirculation Zone Length	Drag Force
Wilcox	0.69 m	932 N/m
k-ε	0.65 m	1027 N/m
Spalart	0.56 m	1112 N/m







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Conclusions from GTS 2D grid studies

- Previous 3D mesh had y^+ too large
  - medium mesh: y^+ max = 10
  - coarse mesh: y^+ max = 20?
- New 2D hyperbolic mesh for y^+ study (no tunnel)
  - Wilcox k-ω will not run with $y^+ > 2$
  - k-ε and S-A will run with $y^+ > 1$, but accuracy suffers
  - pressure not as sensitive to y^+ as shear stress
- Spalart-Allmaras predicts:
  - shorter recirculation zone
  - higher drag
- Wilcox k-ω predicts:
  - longer recirculation zone
  - lower drag

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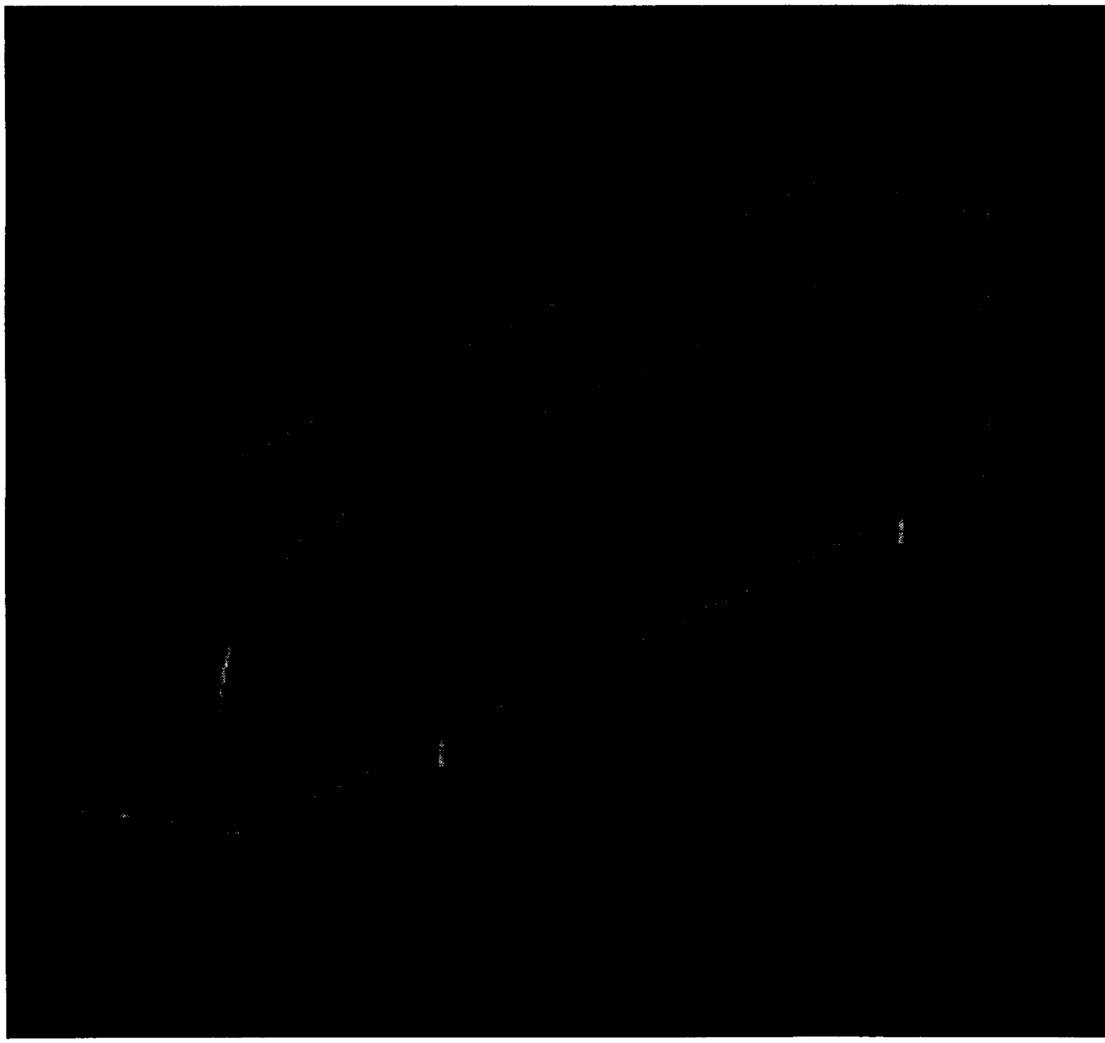
Task 1: New 3D Grid for GTS



- New 3D meshes complete
  - Coarse (300,000 cells)
  - Medium (2.5 million cells)
  - Fine (20 million cells)
- Grid needs to be decomposed (parallel)
- Will run:
  - k-omega/Wilcox
  - Spalart-Allmaras
  - k-epsilon (time permitting)

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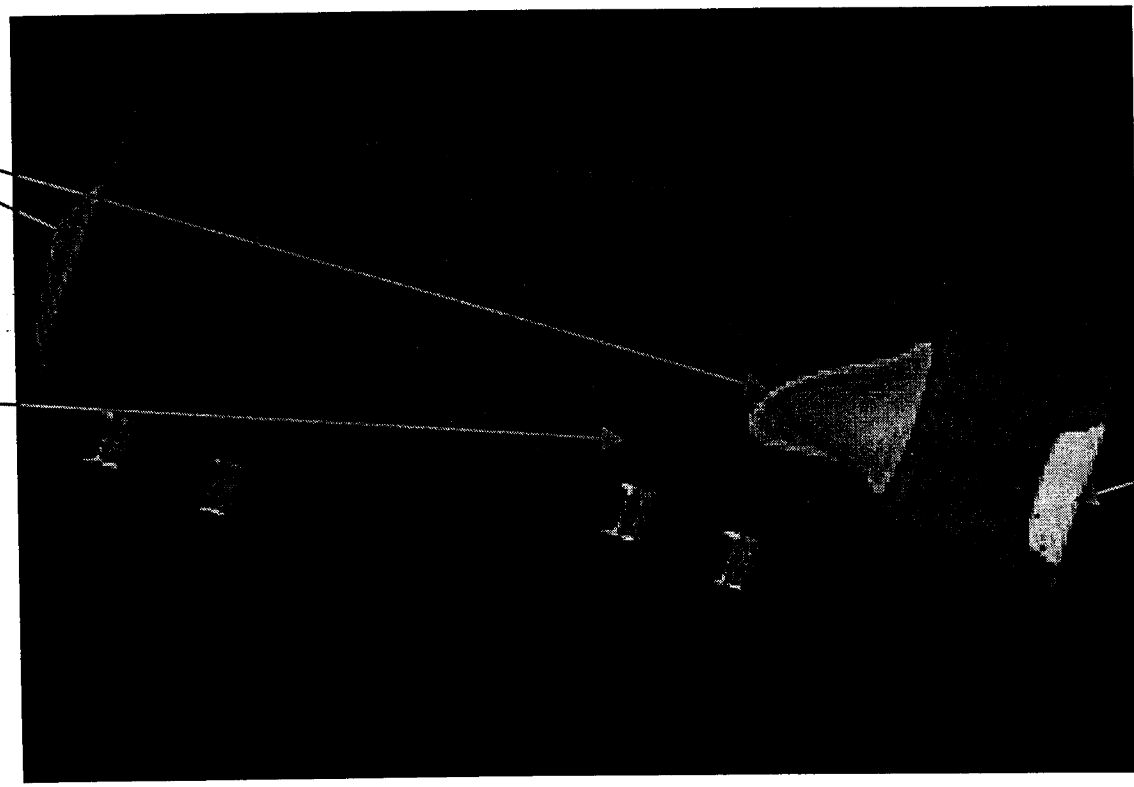
Task 6: GTS, 10 Degree Yaw Solution Spalart-Allmaras, FY01 Medium Mesh

FY01 Medium Mesh is 12 million grid point mesh that Kambiz and Mary completed last year

Negative u-component of Velocity



GTS: 10 Degree Yaw Solution Spalart-Allmaras, FY01 Medium Mesh

Windward side

Leeward side

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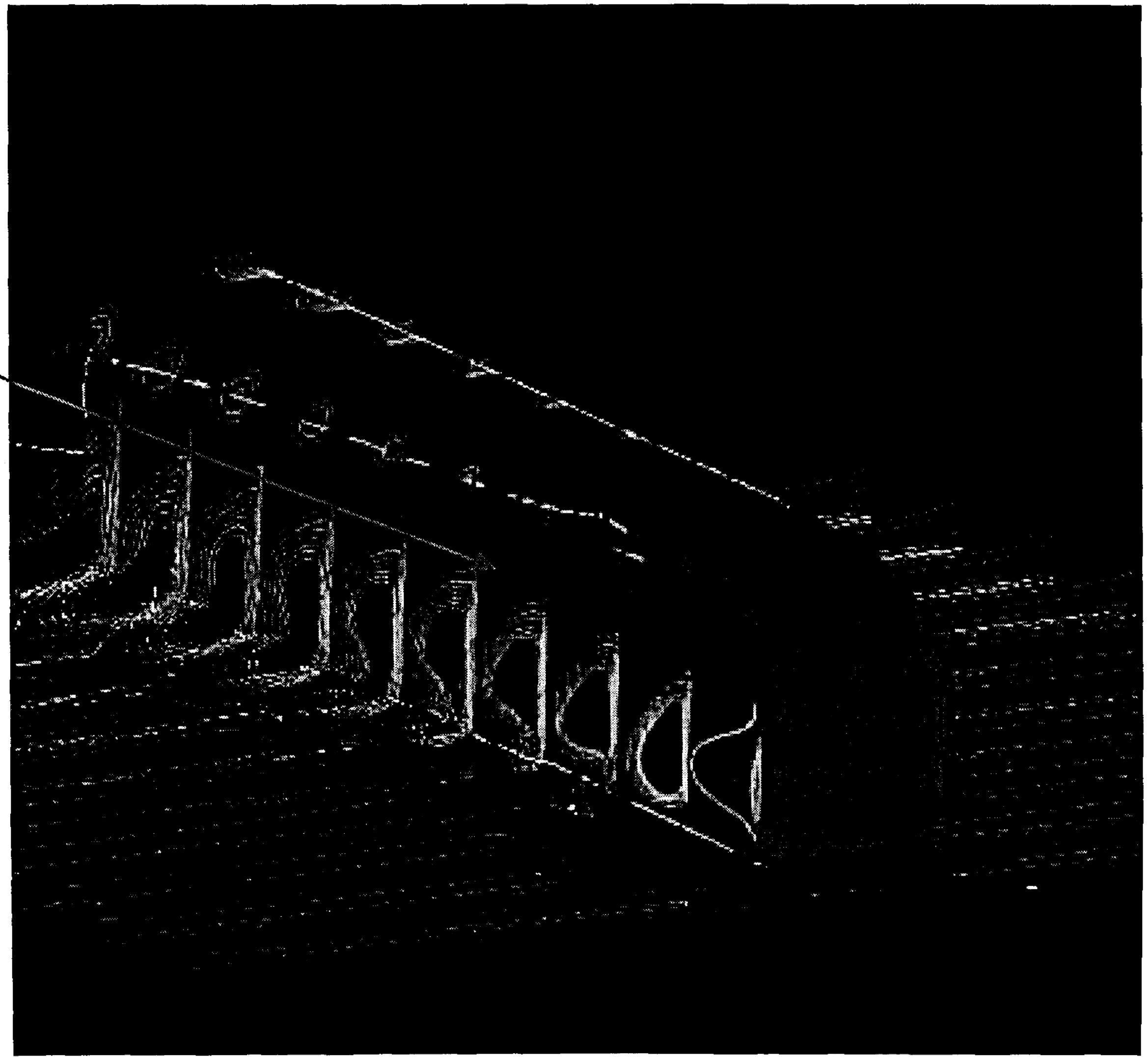
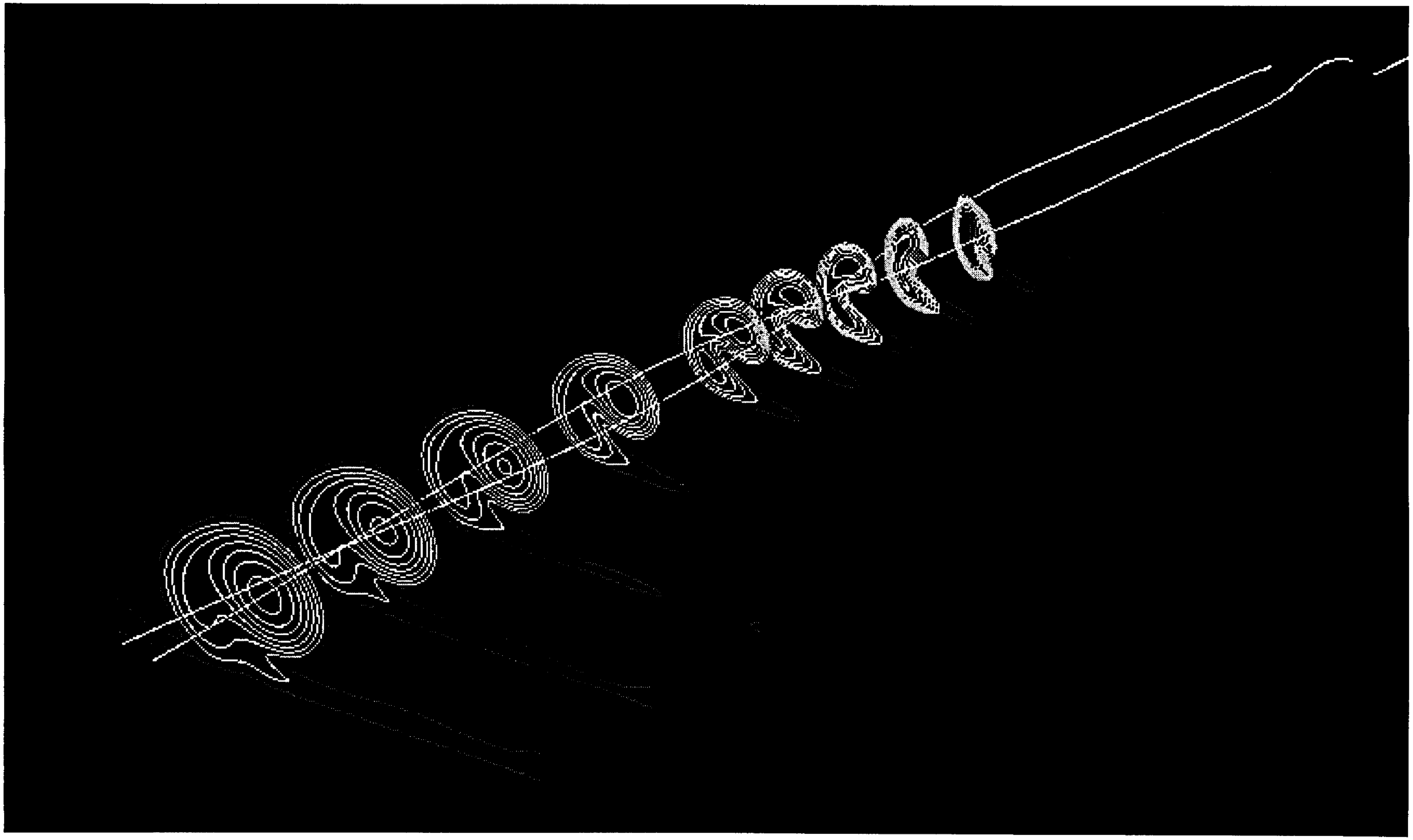
Spalart Allmaras, 10 Yaw, FY01 Medium Mesh
Total Viscosity and Vortex Cores



Spalart Allmaras, 10 Yaw, FY01 Medium Mesh
Total Viscosity and Streamlines



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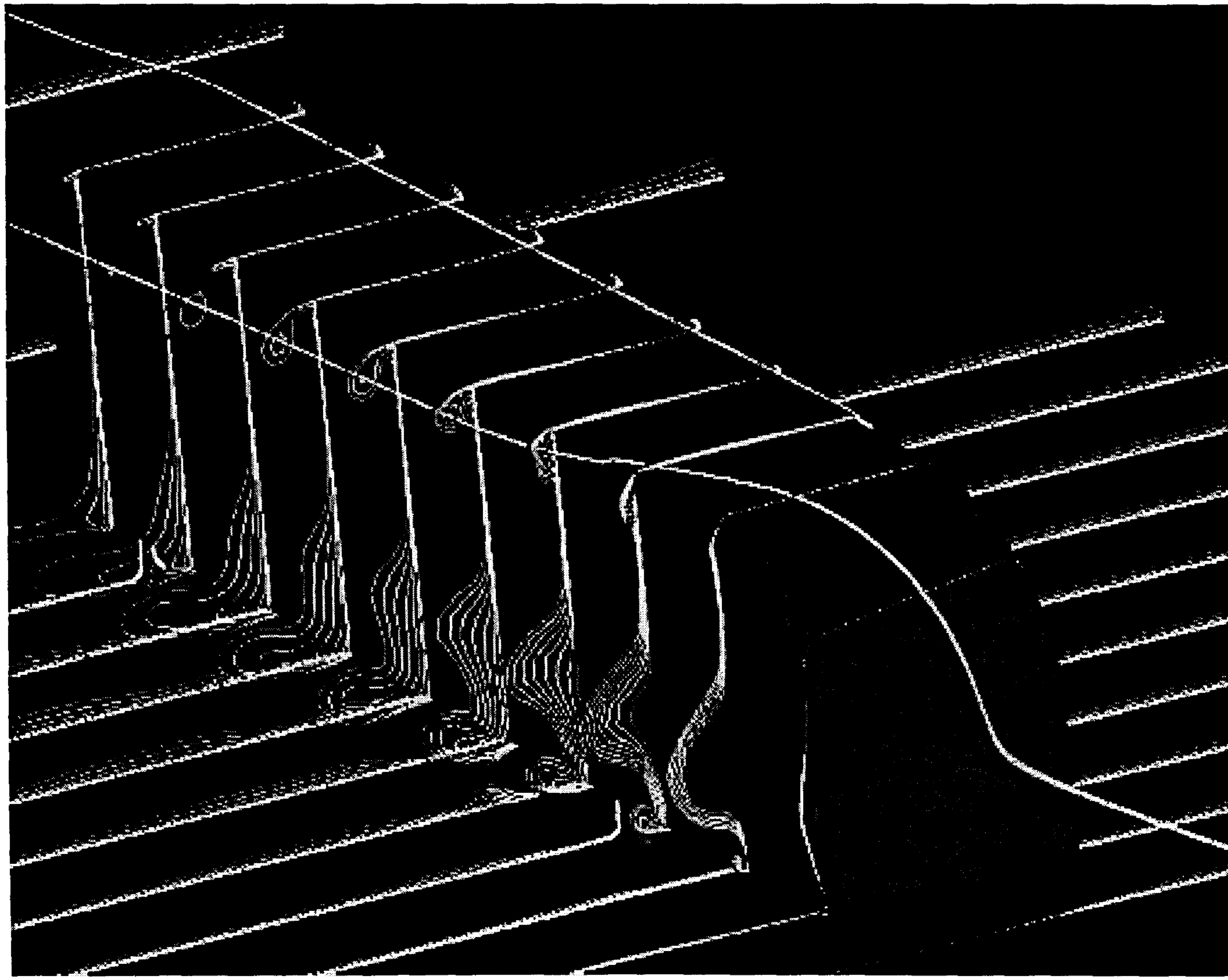
Spalart Allmaras, 10 Yaw, FY01 Medium Mesh Temperature and Streamlines



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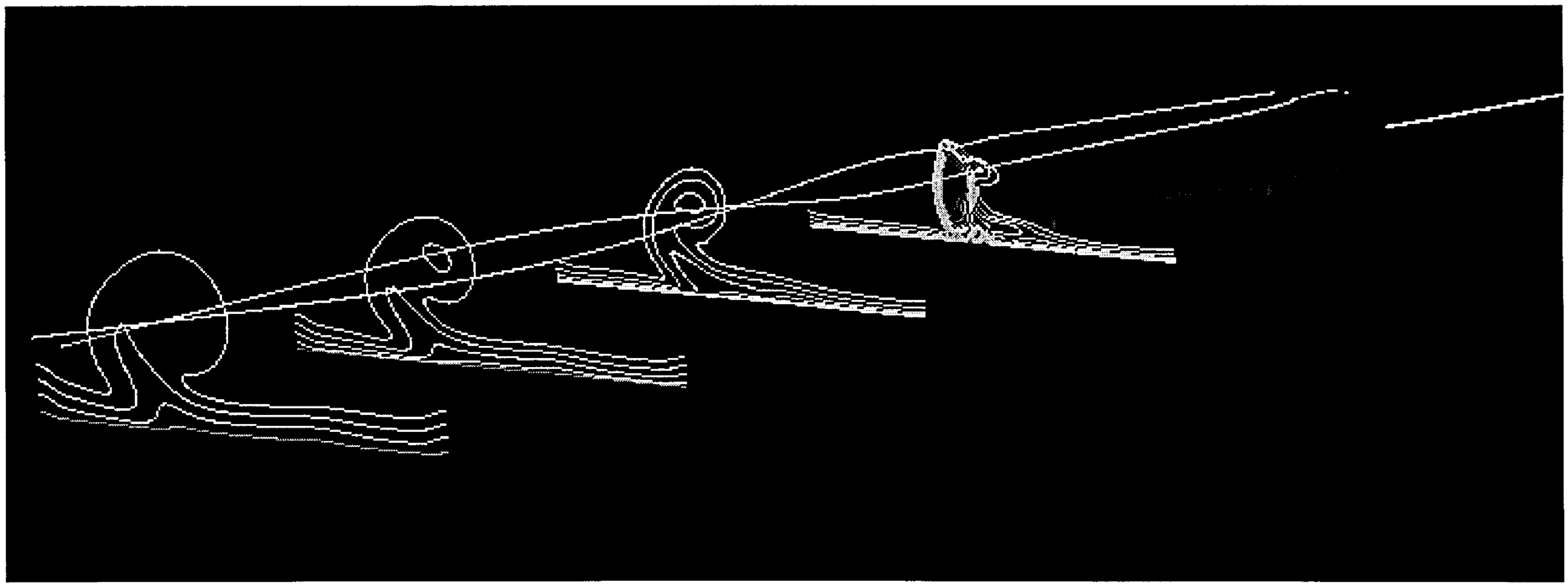
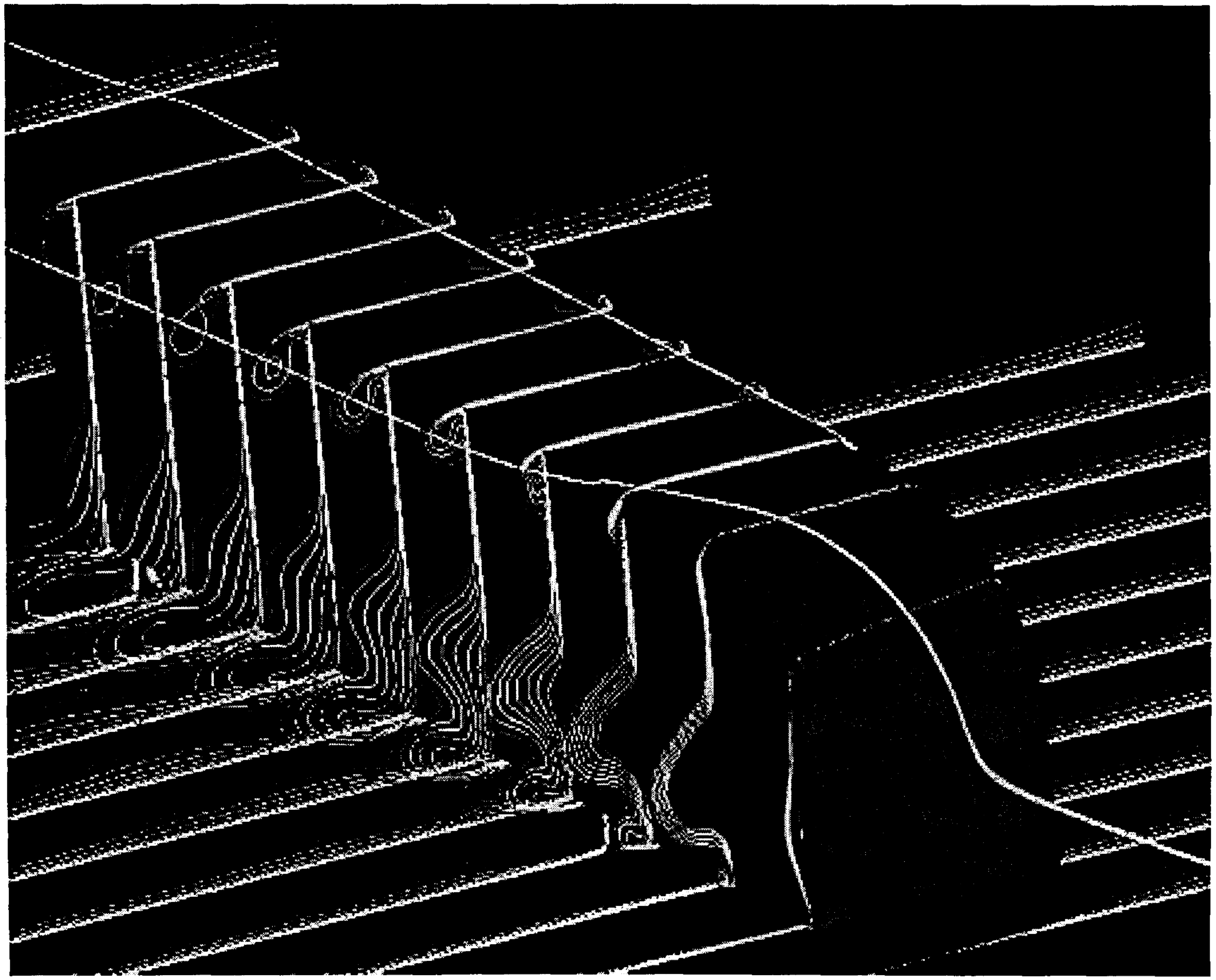
Spalart Allmaras, 10 Yaw, FY01 Medium Mesh Temperature and Vortex Cores



Spalart Allmaras, 10 Yaw, FY01 Medium Mesh
Mach Number and Streamlines



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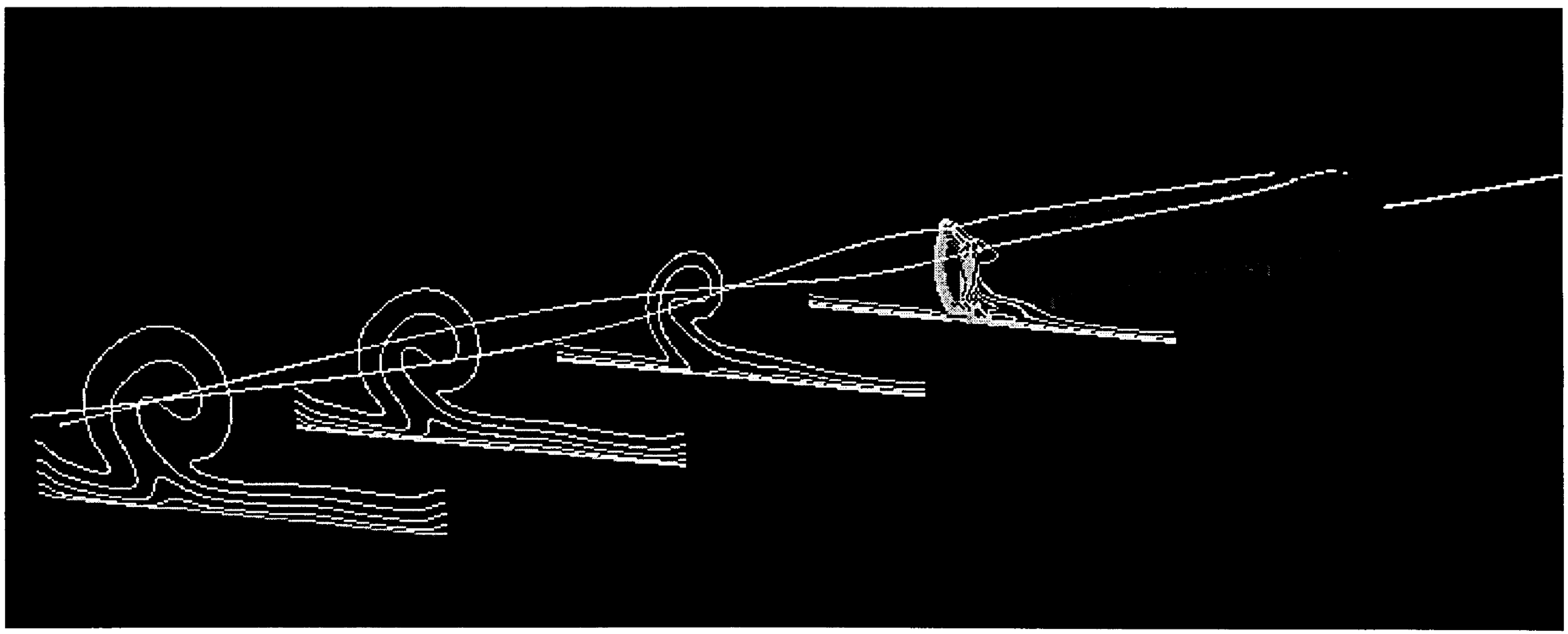
Spalart Allmaras, 10 yaw, FY01 Medium Mesh
Mach Number and Streamlines



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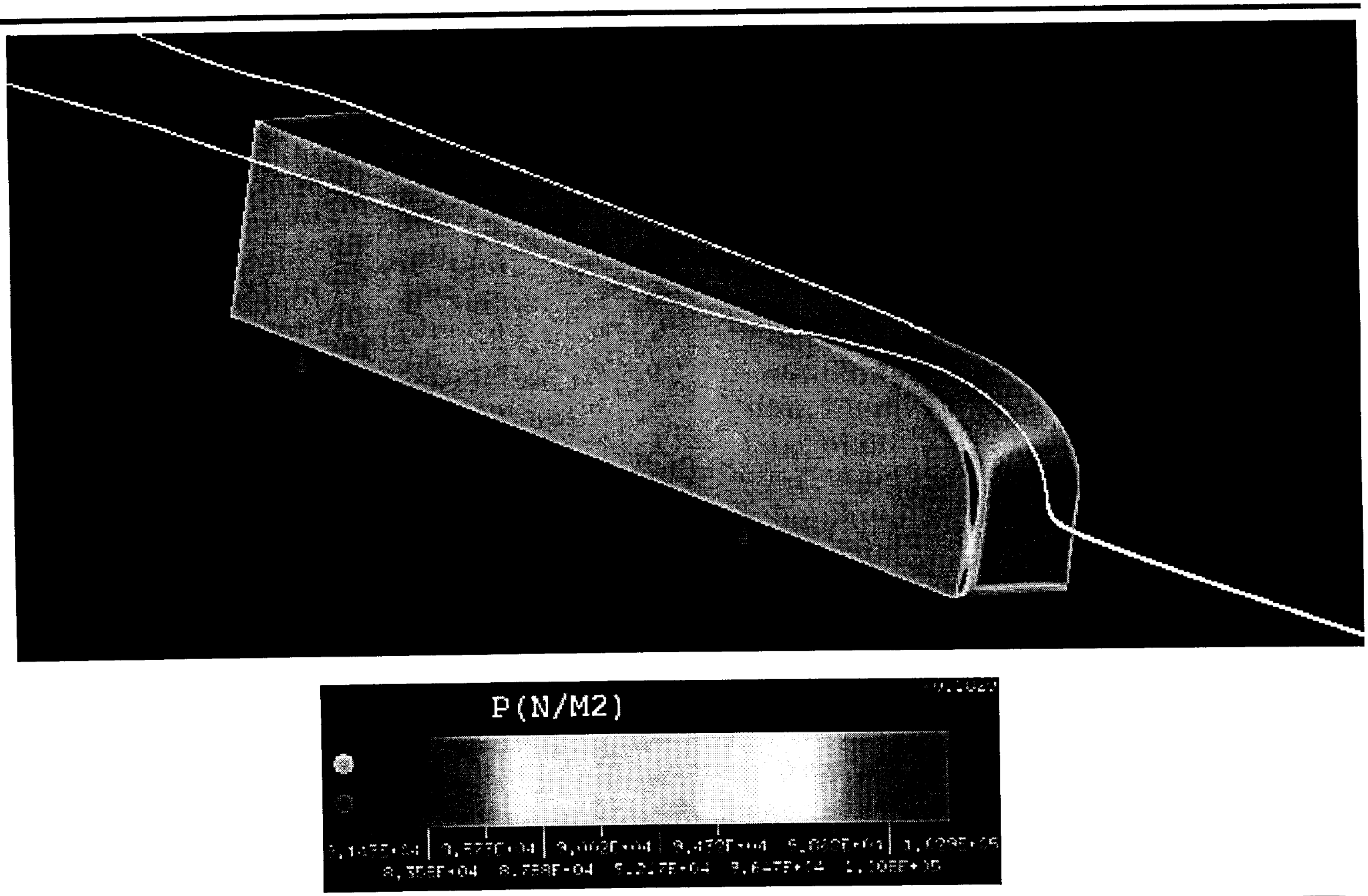
Surface Pressure



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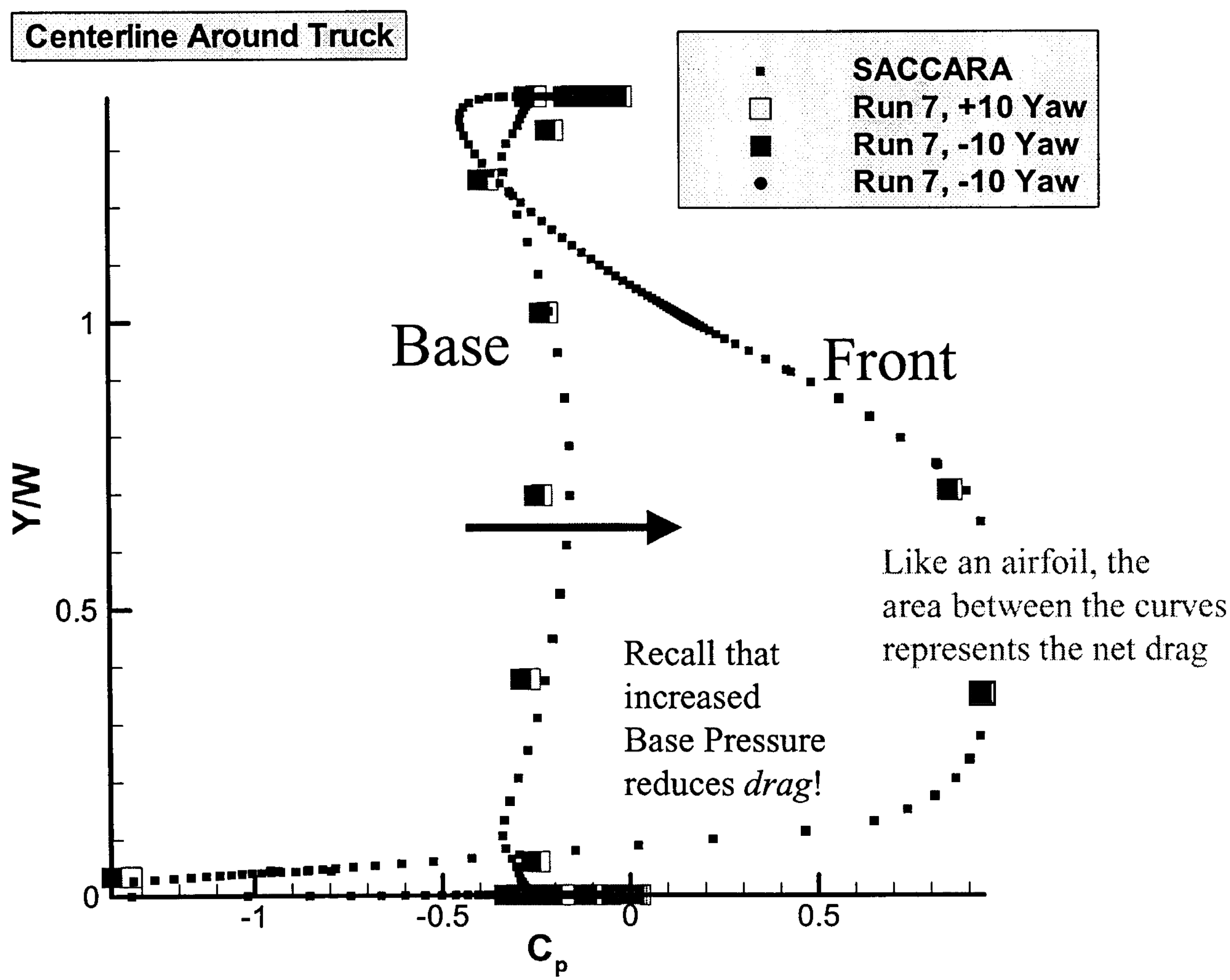
Spalart-Allmaras, 10 Yaw, FY01 Medium Mesh, Vertical Cut



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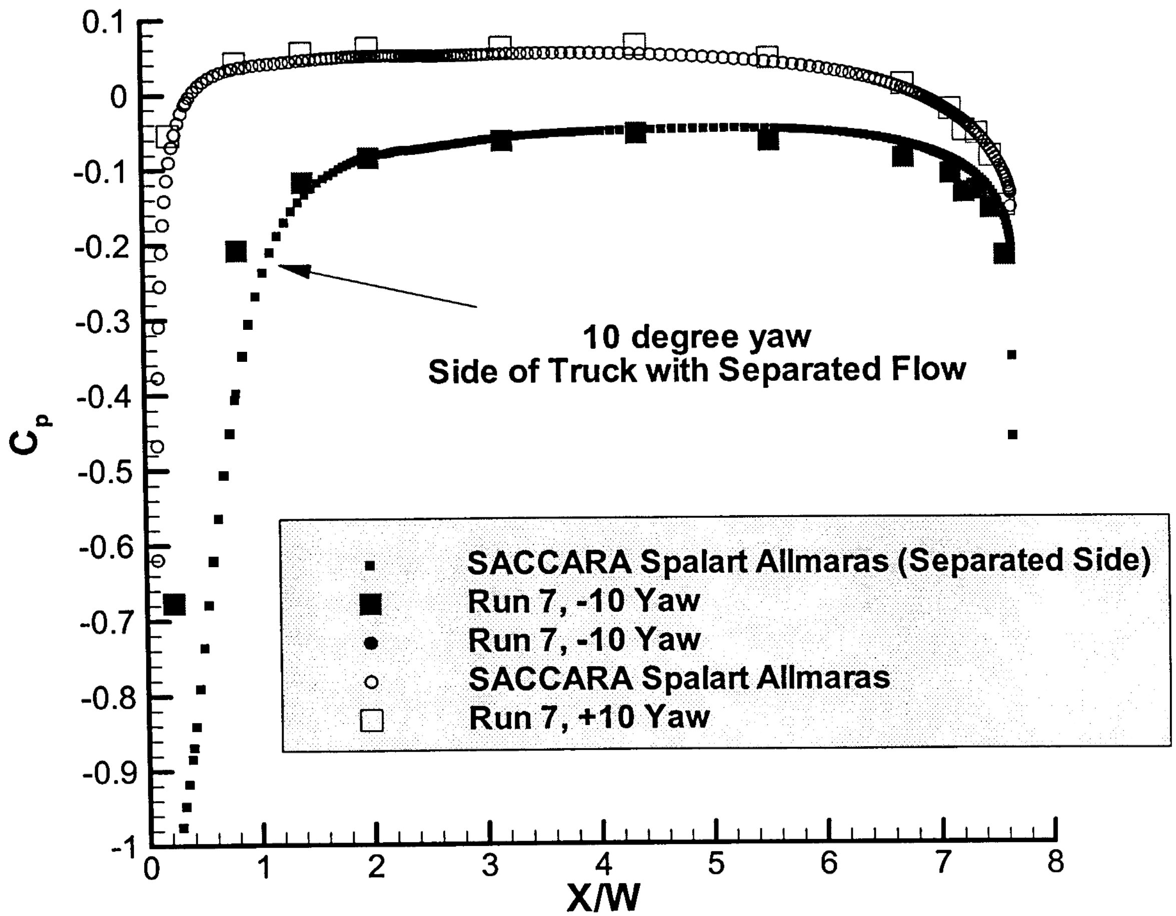
Spalart-Allmaras, 10 Yaw, FY01 Medium Mesh, Horizontal Cut



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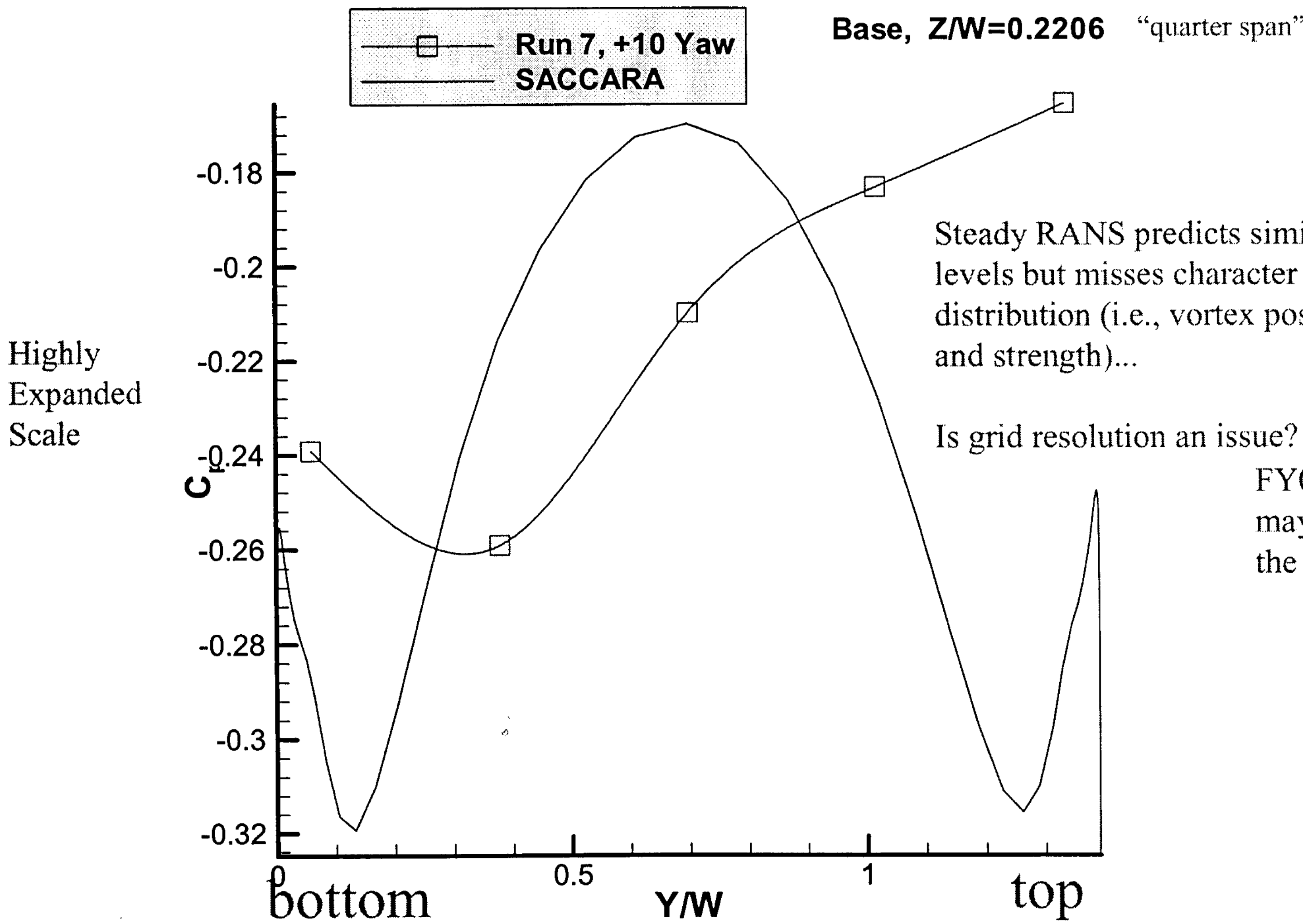
Spalart-Allmaras, 10 Degree Yaw, FY01 Medium Mesh, Vertical Cut



Steady RANS predicts similar pressure levels but misses character of distribution (i.e., vortex position and strength)...

Is grid resolution an issue?

FY02 grids may answer the grid question

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Spalart Allmaras, 10 Degree Yaw, FY01 Medium Mesh

10 Degree Yaw
Wind Axis Force Coefficients

		C_D	C_S
SACCARA	10^{o} yaw	0.6679	1.2210
Experiment (Run 7) Wall Reference[a]	10^{o} yaw	0.5055	1.1833
	-10^{o} yaw	0.5197	-1.0865
	-10^{o} yaw	0.5202	-1.1039
Experiment (Run 7) Upstream Reference[b]	10^{o} yaw	0.54	1.2640
	-10^{o} yaw	0.5543	-1.1360

Numerical C_D used wall reference pressure to compute freestream dynamic pressure

a. Static pressure reference is measured at wall pressure tap.

b. Static pressure reference is measured upstream of test section.

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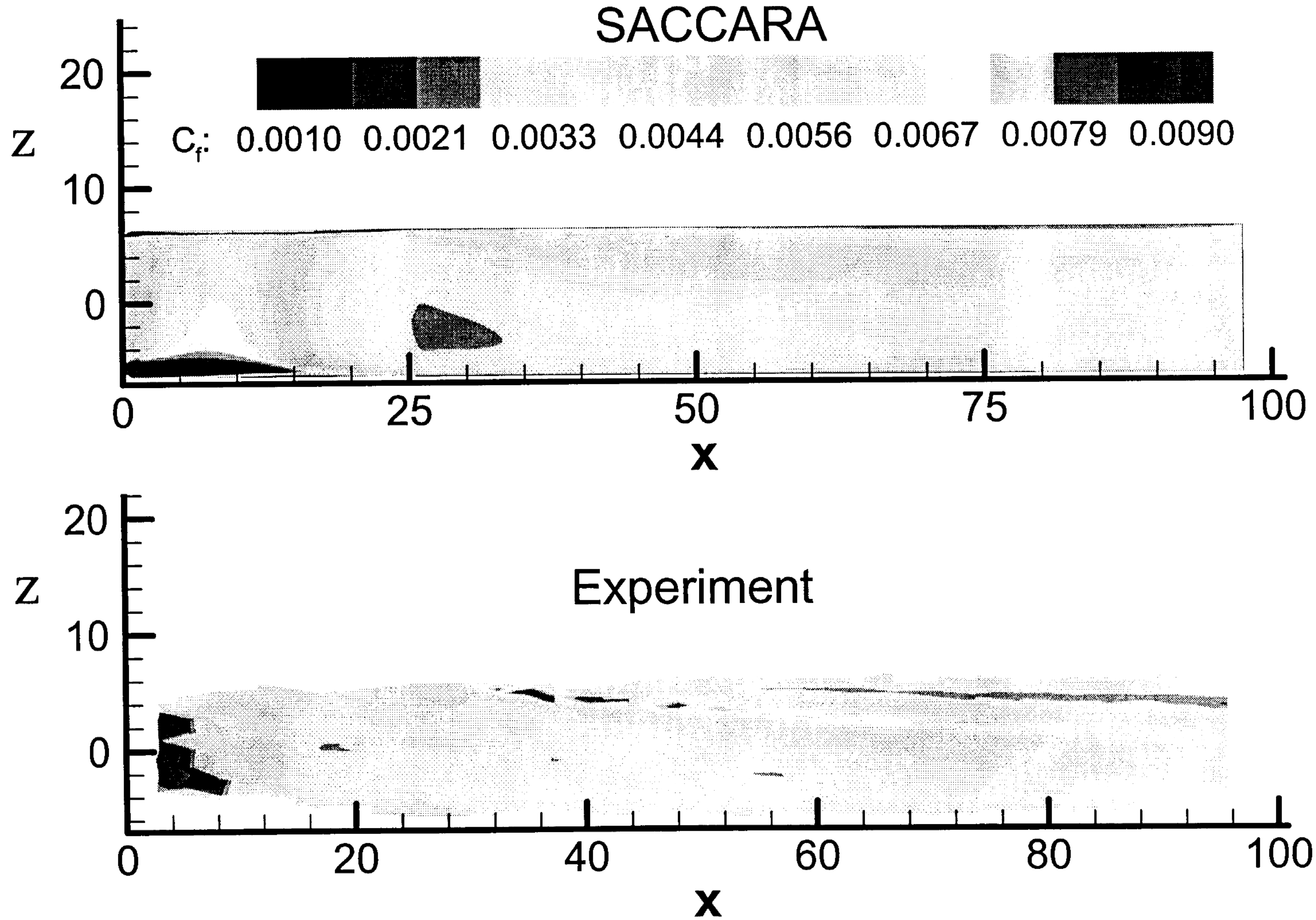
Skin Friction on Top, 10 Degree Yaw Spalart-Allmaras Compared with Experiment



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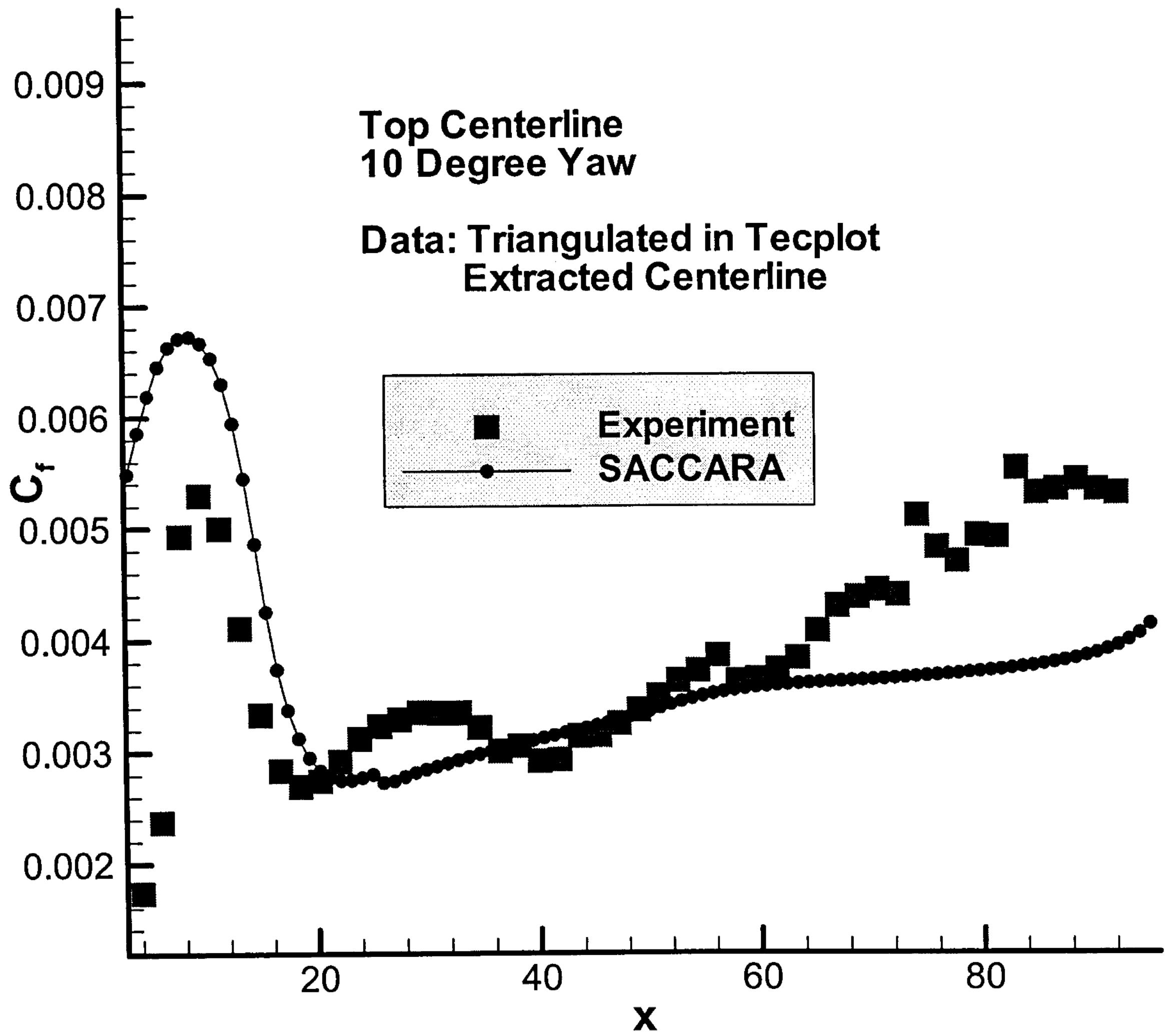
Skin Friction on Top, 10 Degree Yaw Spalart-Allmaras Compared with Experiment



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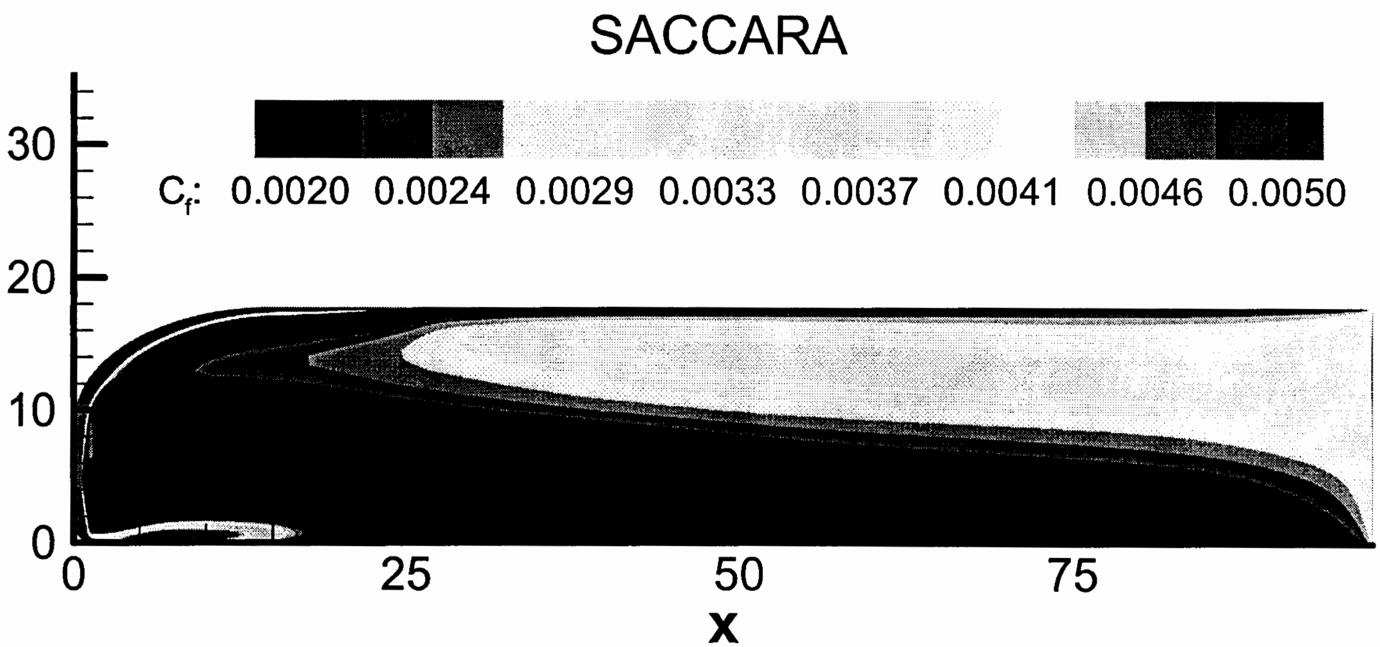
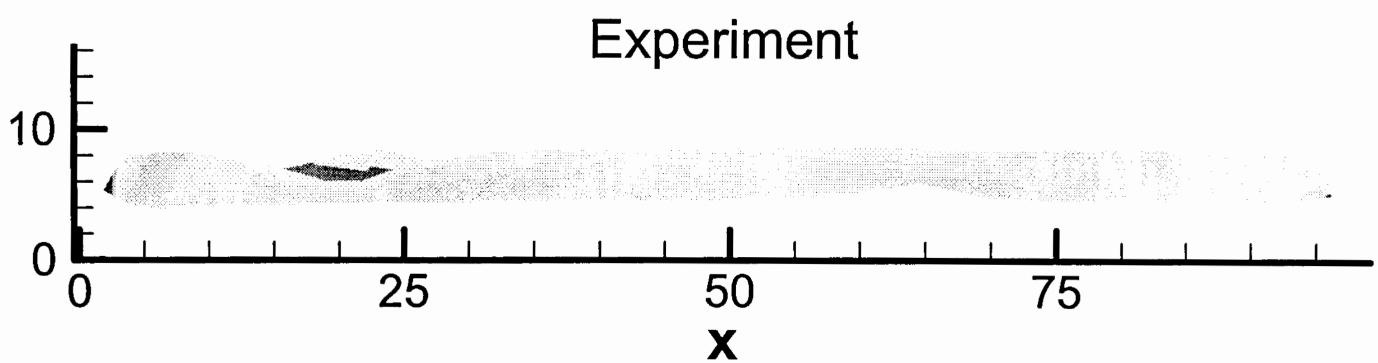
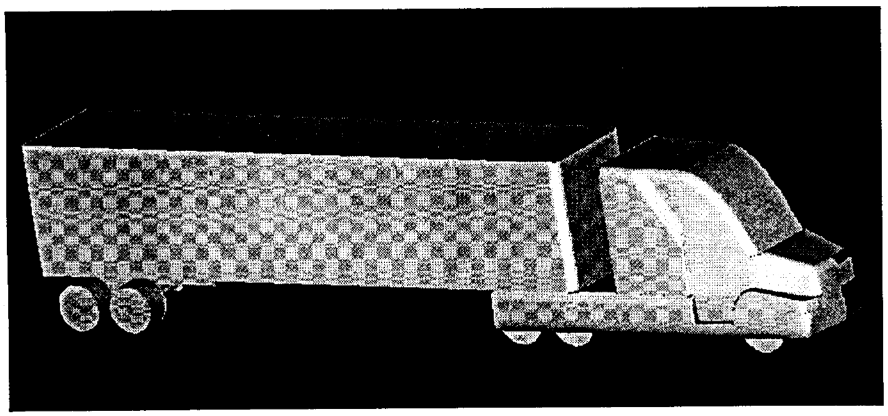
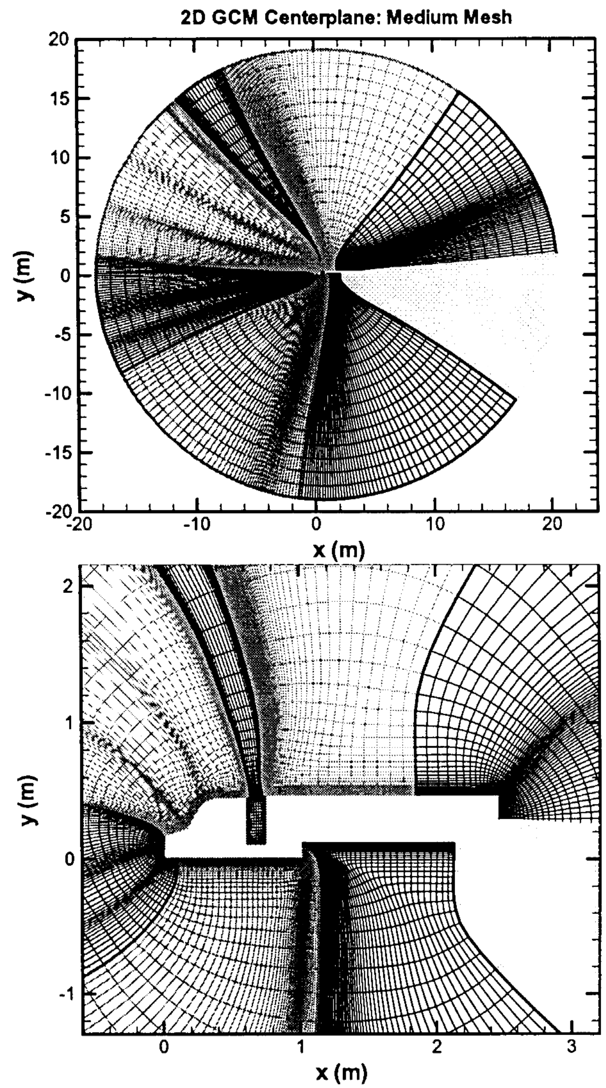
Skin Friction on Lee Side, 10 Degree Yaw Spalart-Allmaras Compared with Experiment





GCM: 2D Studies





- Meshes generated (centerline cut)
- k-omega/Wilcox solution obtained
- y+ values determined

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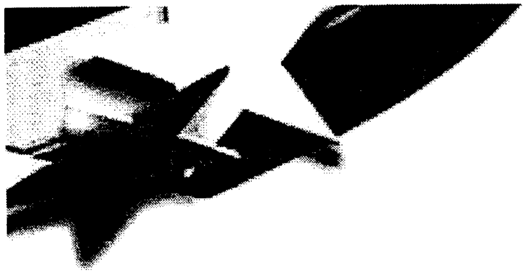
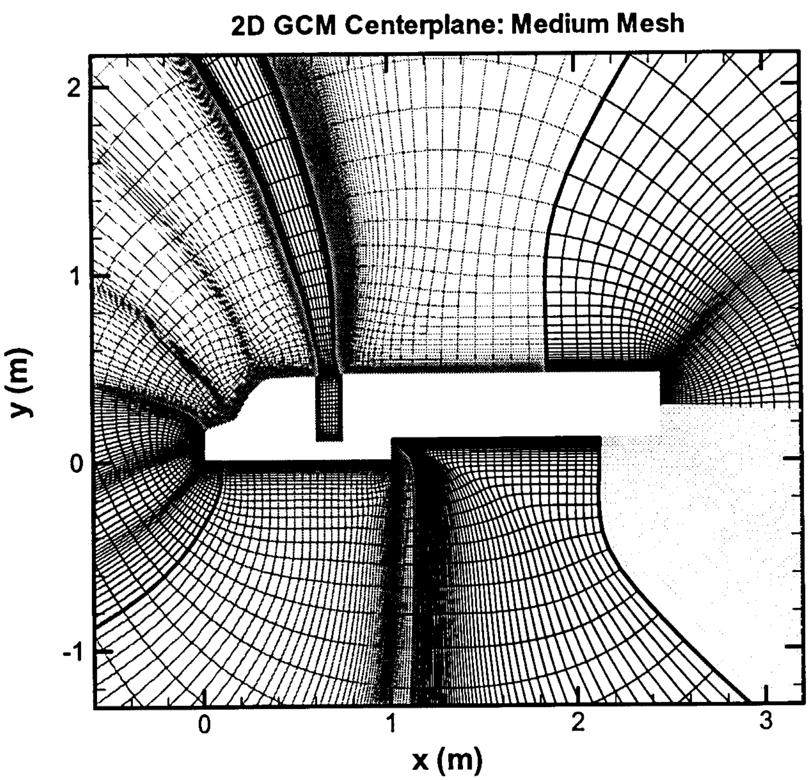
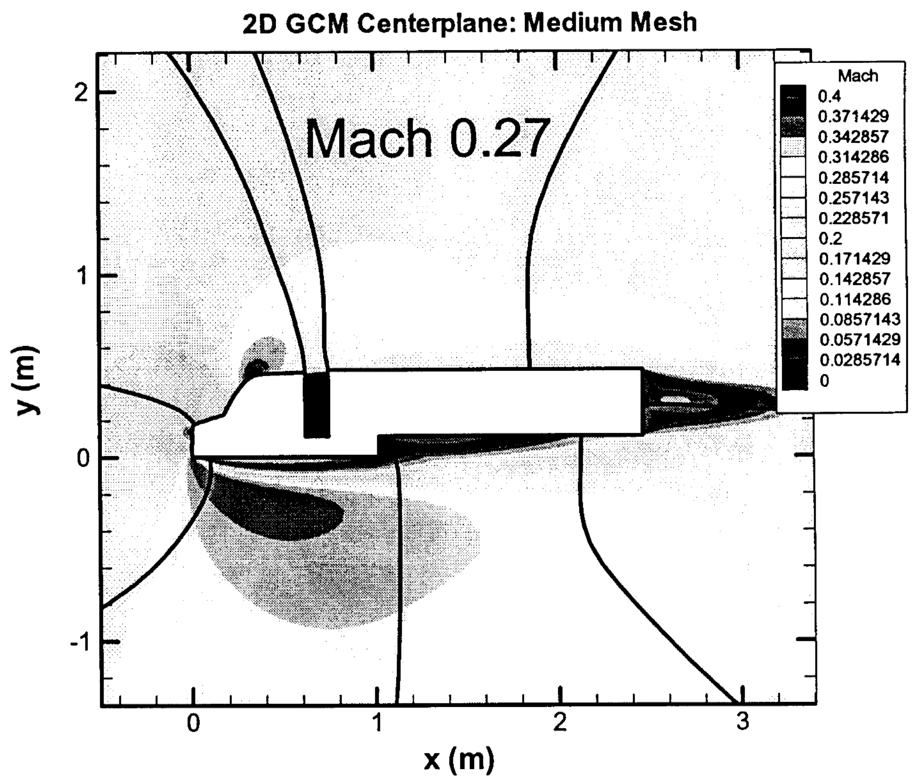


GCM: 2D Studies



Grid



Mach Contours

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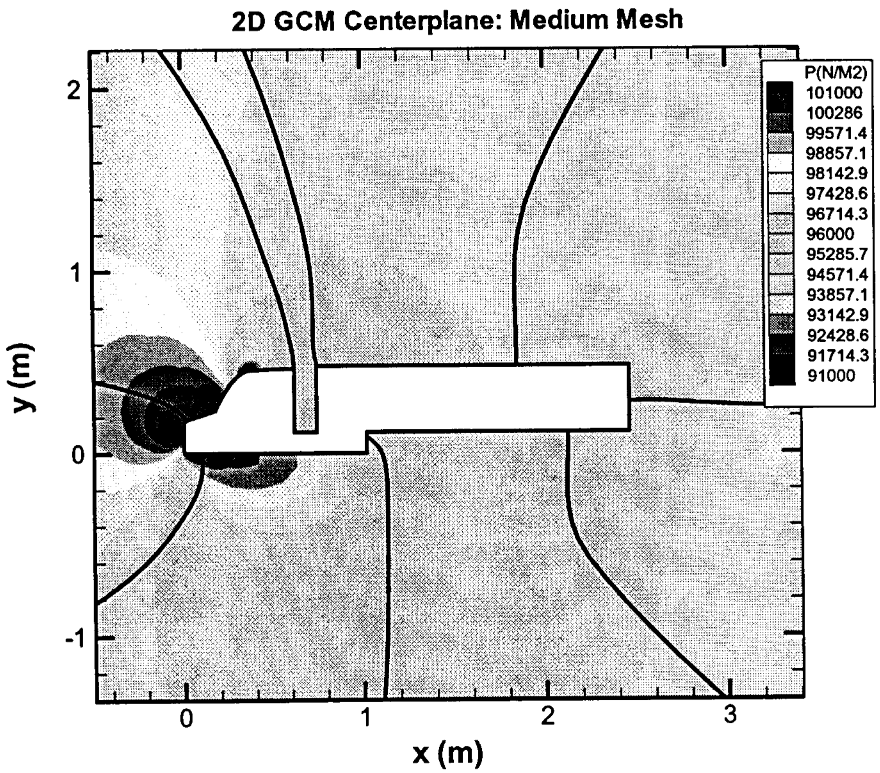
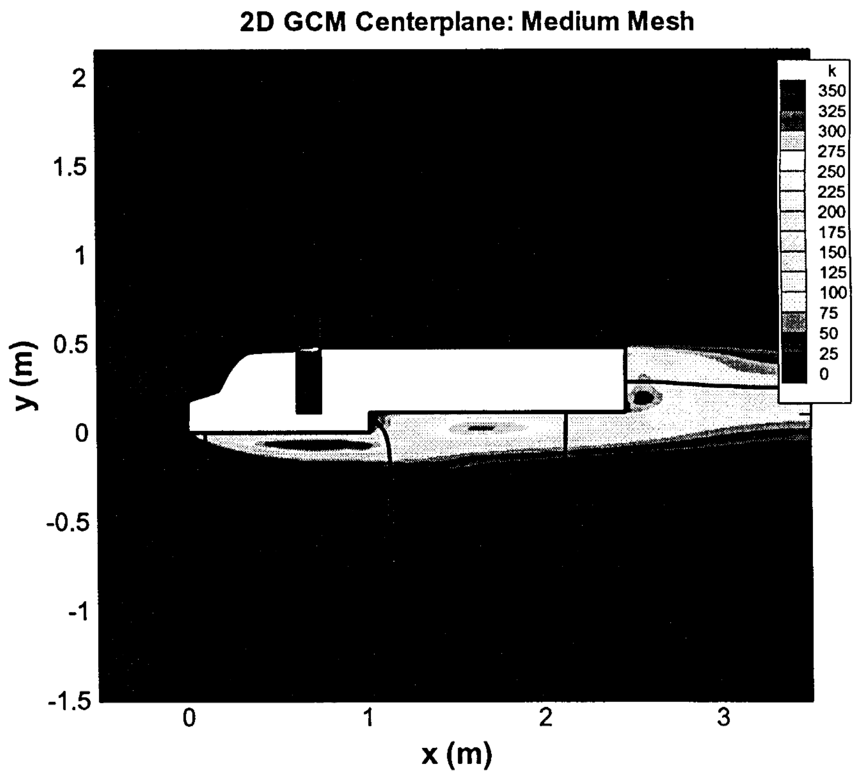
GCM: 2D Studies



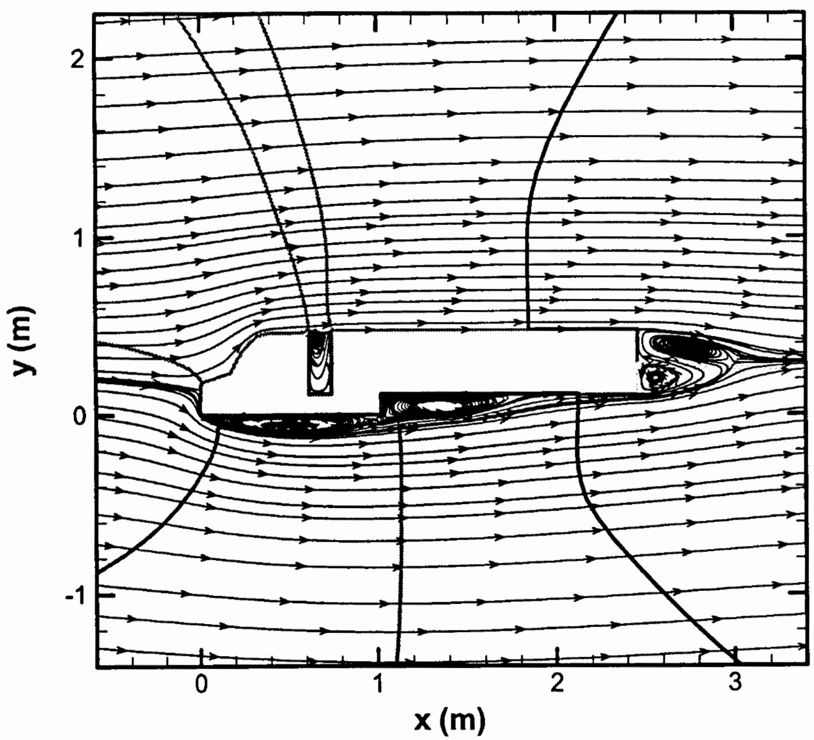
Pressure Contours

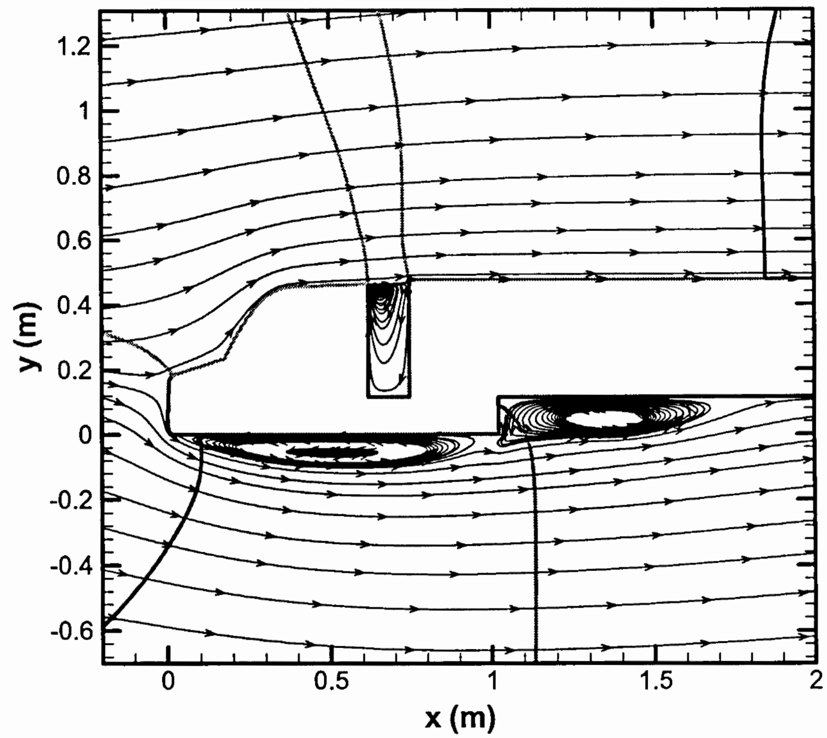


TKE Contours

Sandia National Laboratories

GCM: 2D Studies





Streamlines

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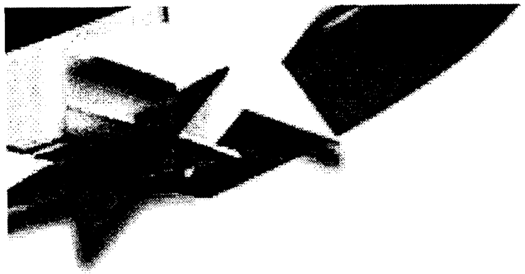
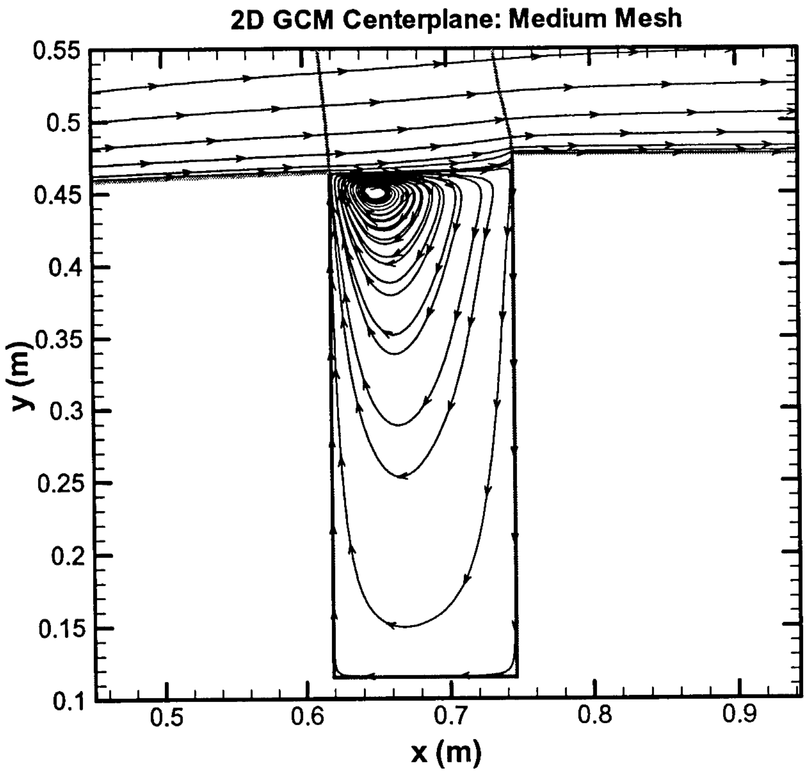
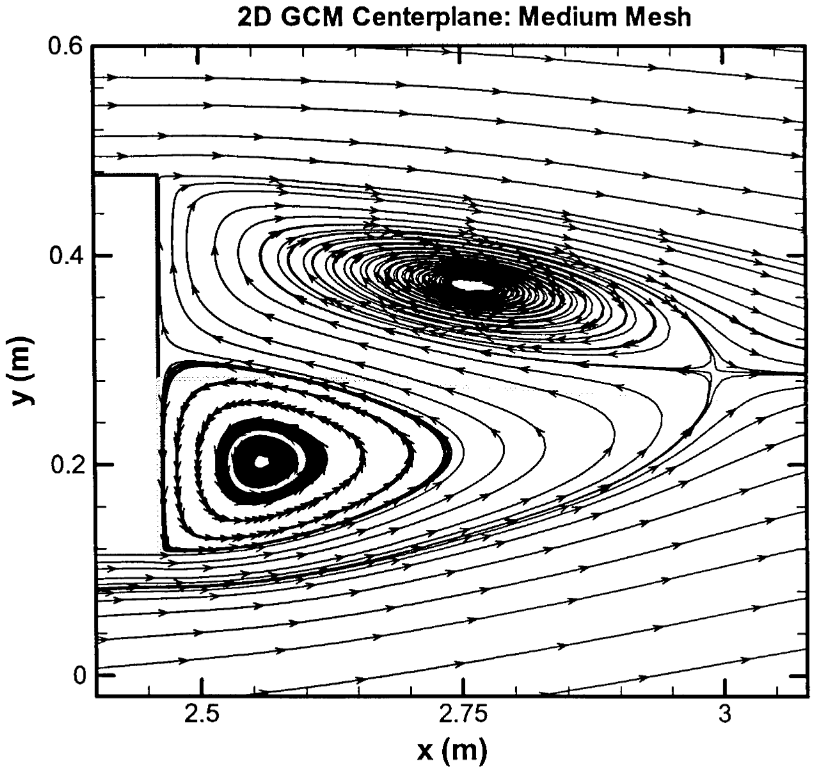


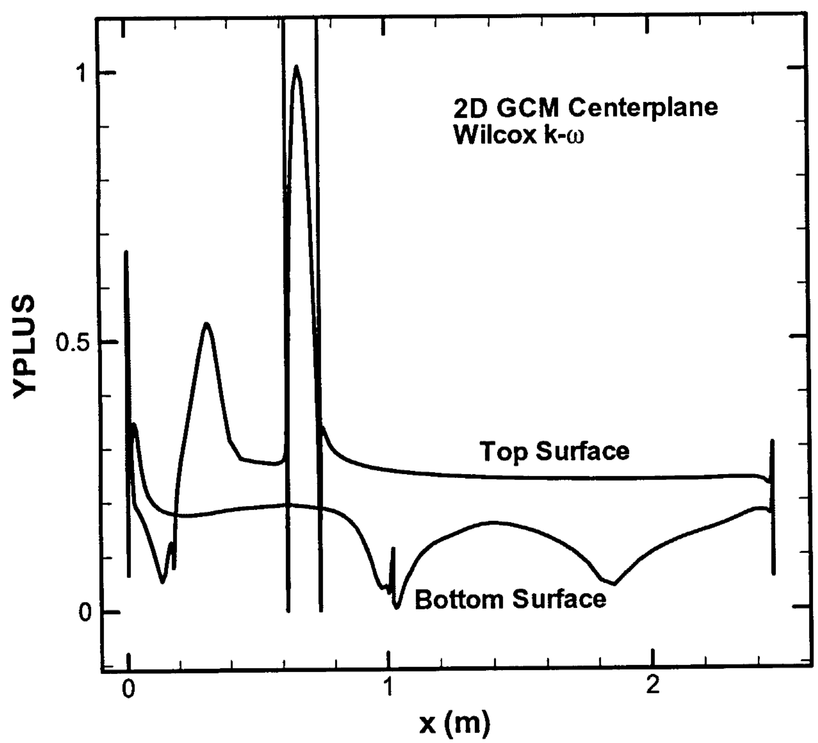
GCM: 2D Studies



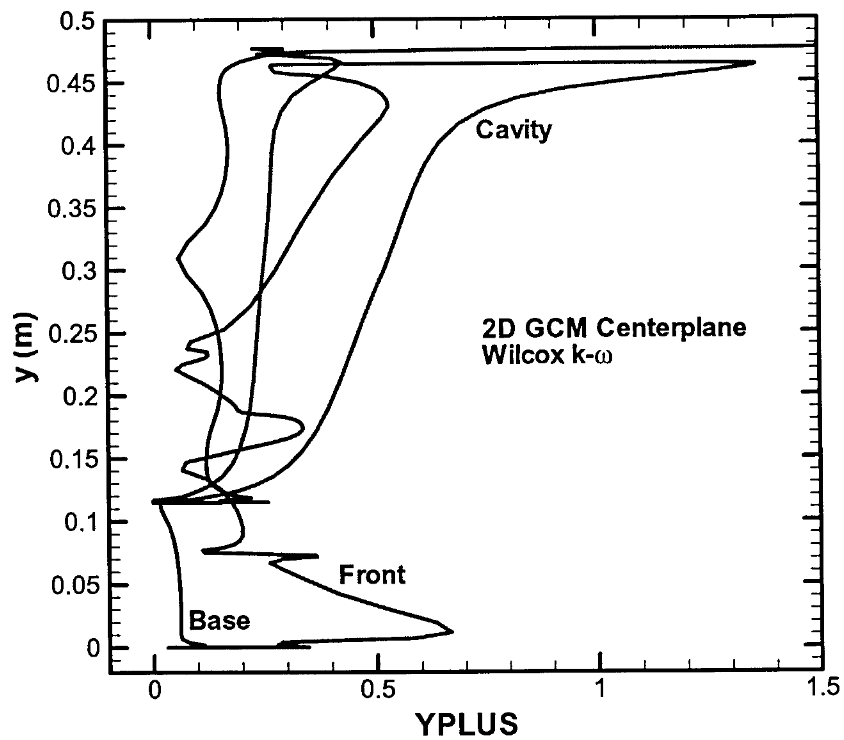


Streamlines

GCM: 2D Studies



y+ (top/bottom)



y+ (front/back)

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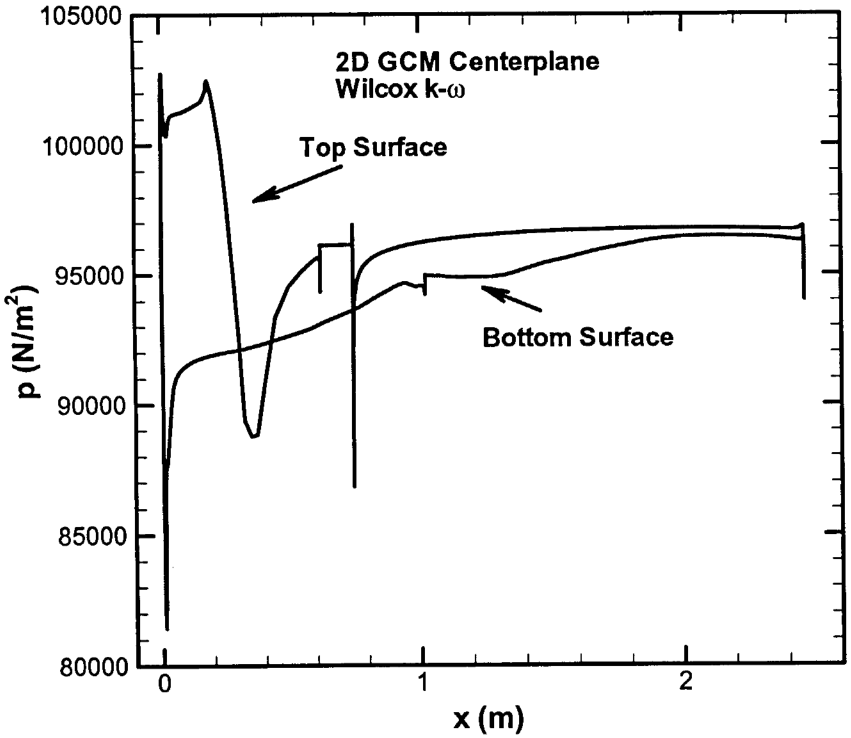
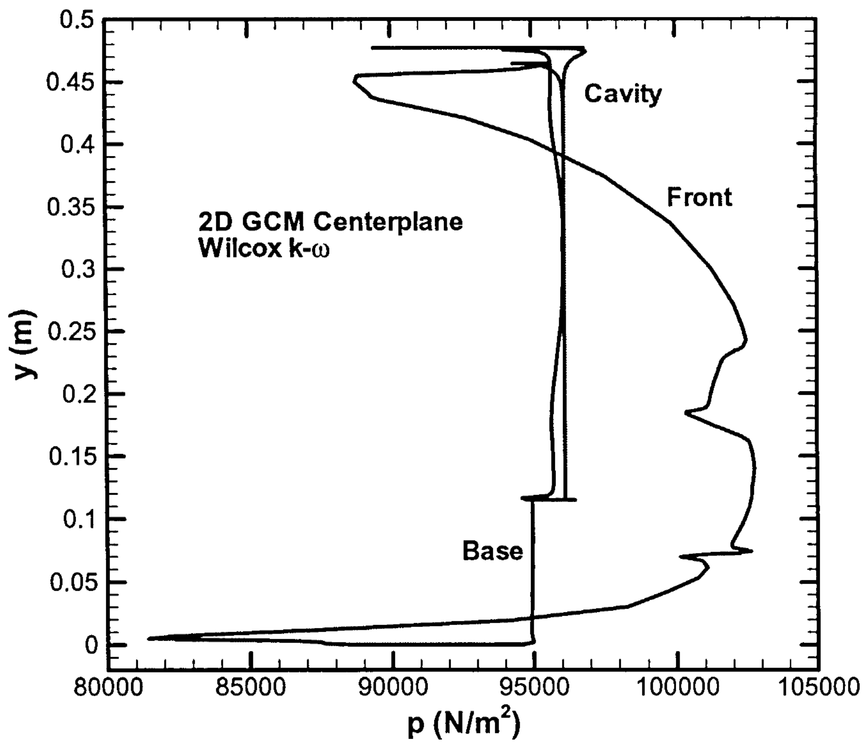
GCM: 2D Studies



Pressure (top/bottom)



Pressure (front/back)

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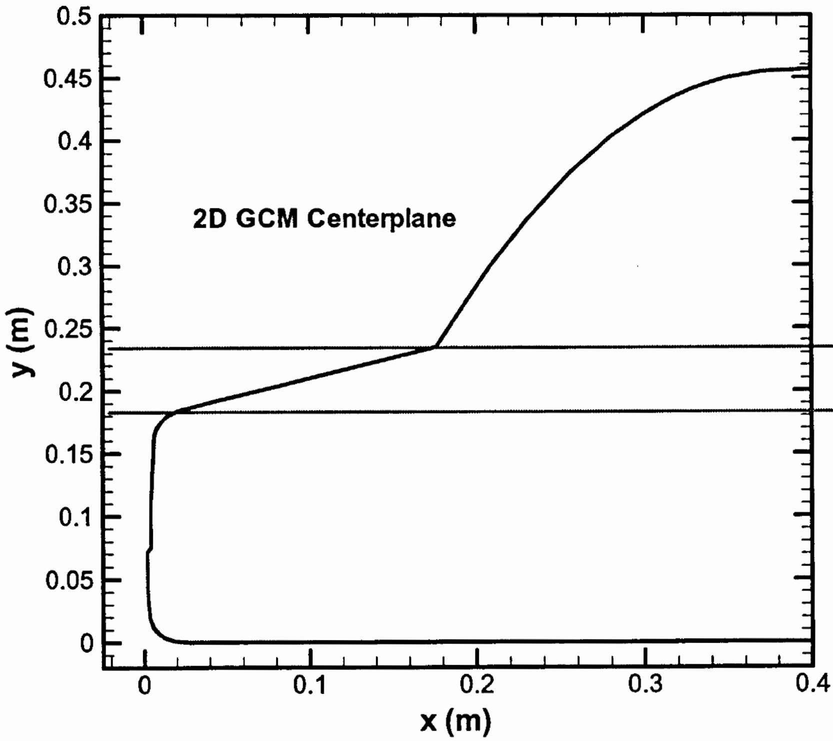
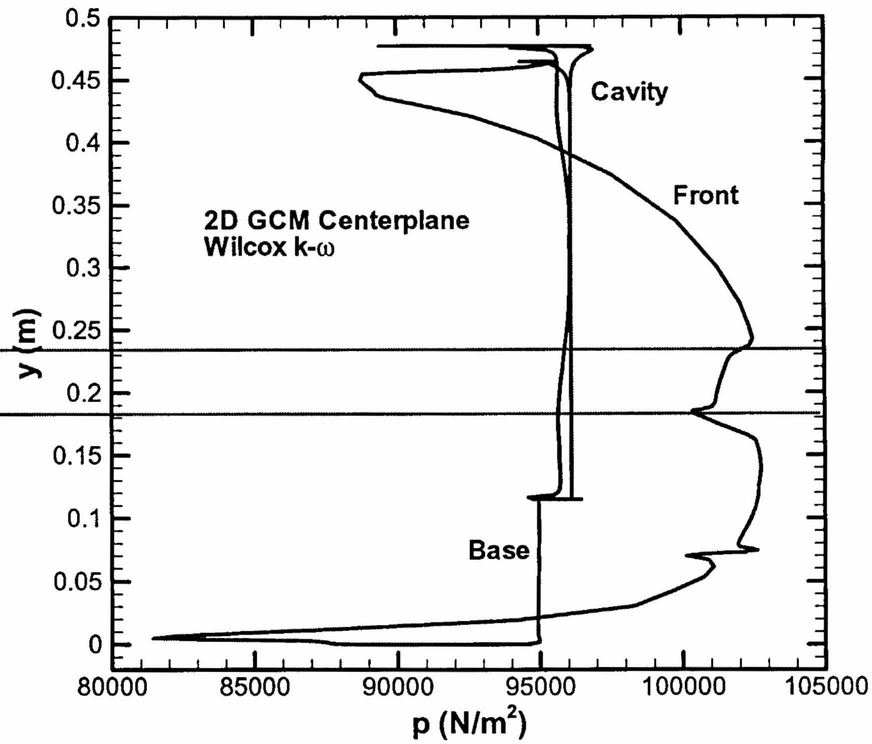
GCM: 2D Studies

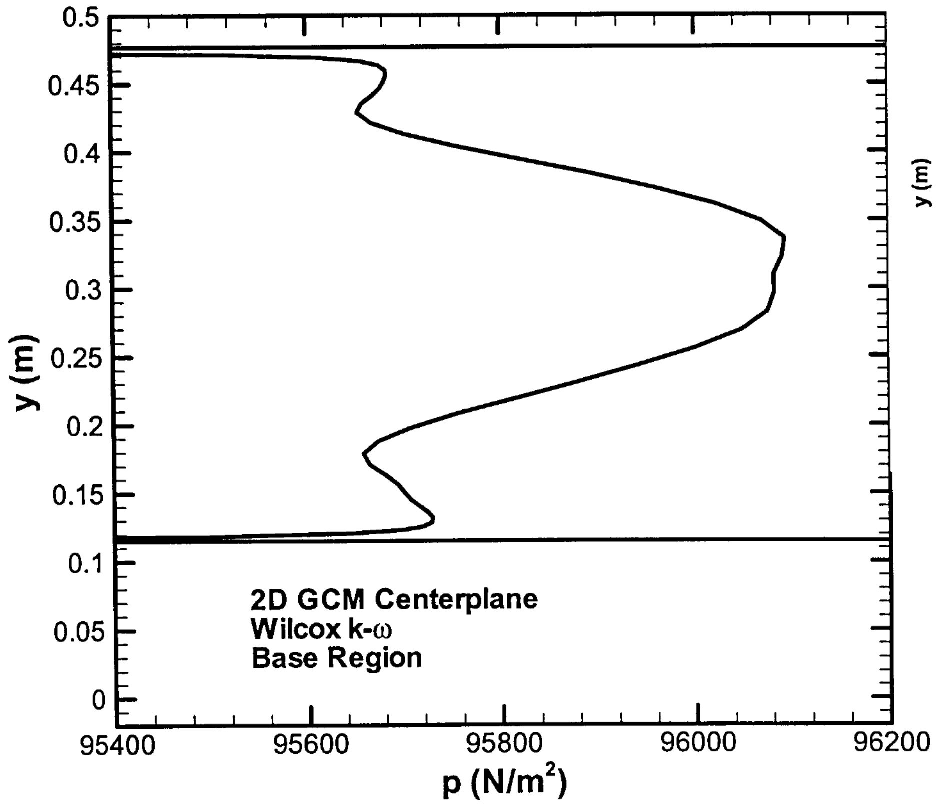


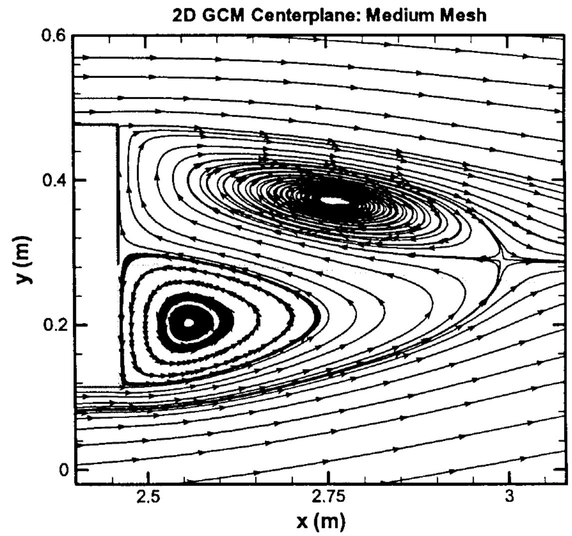


Pressure (front/back)

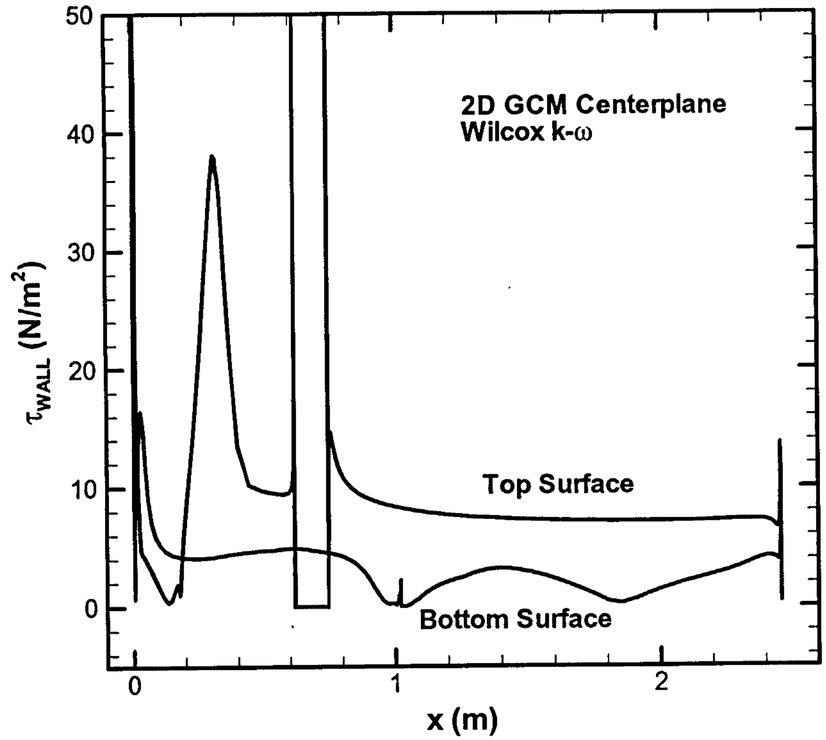
Sandia National Laboratories

GCM: 2D Studies

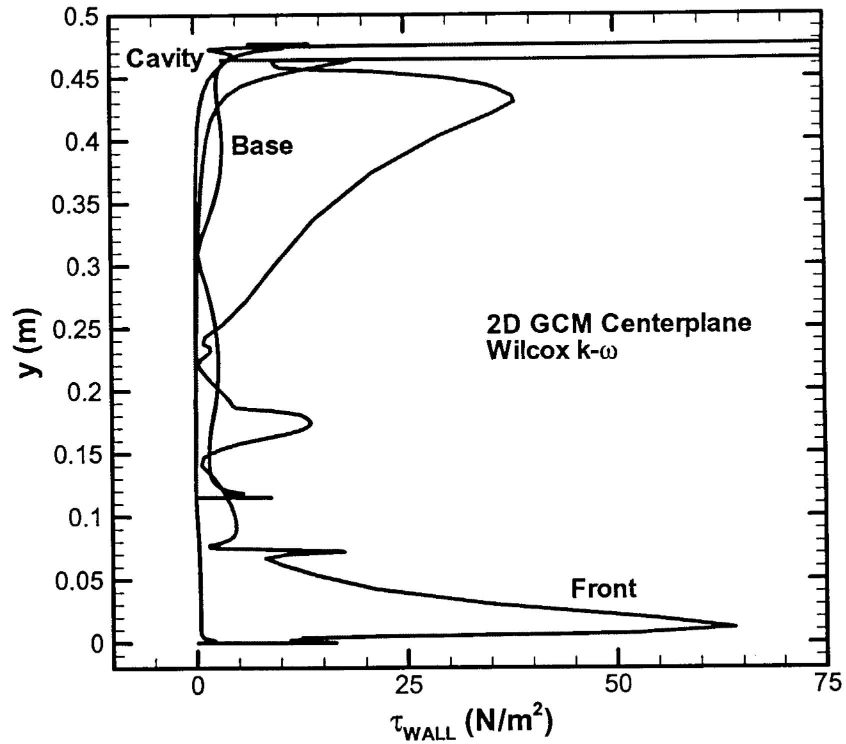




GCM: 2D Studies



Shear Stress (top/bottom)



Shear Stress (front/back)

GCM: 2D Studies

Conclusions

- More complex (and realistic) geometry than the GTS
- Determined appropriate wall spacing based on y+ criteria
- Significant separation on underside of truck
  - below the cab
  - below the trailer
- Underside separation (without ground plane) strongly affects the separated flow in base region
- Additional separation zone in the cab-trailer gap

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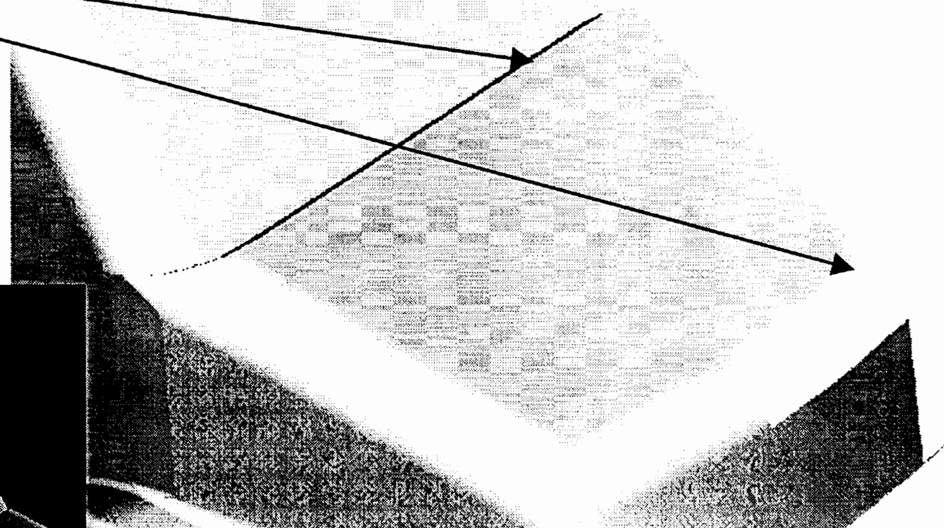
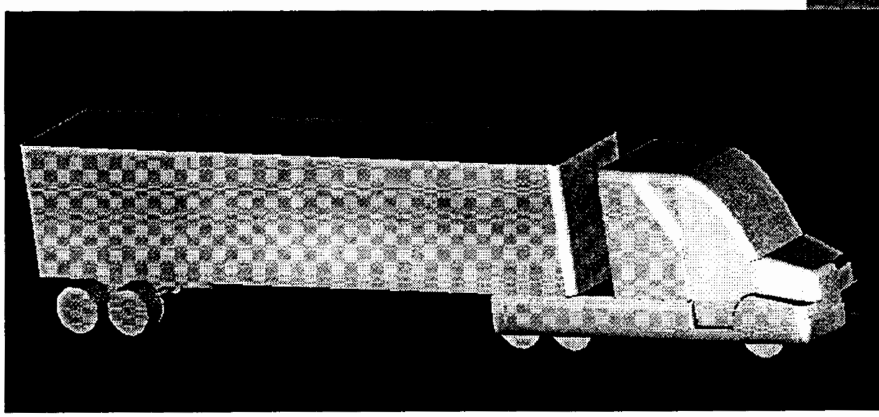
GCM: 3D

- Obtained ProE model
- Half of truck?
- Surfaces still missing
- SNL is reluctant to speculate on missing geometry surfaces





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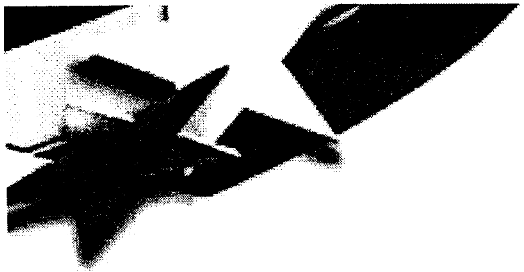


Sandia Leveraging

- Engineering Sciences Research Foundation
  - Transition modeling
  - Hybrid RANS/LES turbulence modeling
- ASCI Material and Physical Models
  - RANS turbulence modeling
- ASCI Code Development
  - Verification and Validation methodologies/procedures
- ASCI University Alliance
  - boundary layer transition research
- ASCI Red Teraflop Computer
  - 9000 processor parallel machine
- Large dataset visualization with Parallel Visual 3
  - Bob Haimes, MIT (feature tracking)
  - data mining

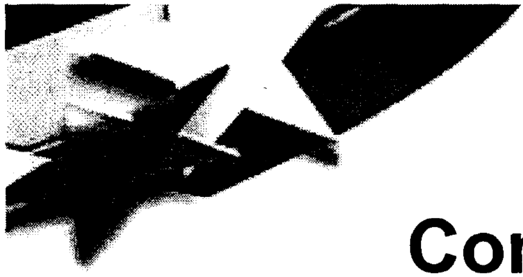
Observations

- RANS for drag prediction only makes sense if the base pressure is accurately modeled...
  - Even high fidelity, “integrate to the wall” models do not show that steady state RANS can cut it (for drag)…
    - Lower fidelity models (e.g., wall functions) designed for wall bounded flows offer no credible expectation that they better model the physics of truck base flows…
  - LES still not practical because of wall treatment
  - Hybrid RANS/LES offers a good possibility for accurate base flow prediction
- Experimental data need to be better understood and documented (NASA is doing this...)
  - Validation experiments should:
    - utilize simplified geometries (start simple and work up)
    - have well characterized freestream conditions
    - quantify uncertainties

Observations (continued)

- Current RANS CFD can be used for vehicle design (e.g., airflow modification) for all surfaces (top, bottom, sides, front) except base
  - can optimize pressure distributions to modify aerodynamic forces for large portions of the vehicle (if used carefully)

- Industry needs our help connecting CFD with Aerodynamics and design (not just in terms of fluid mechanics): *"What does it mean to me and how can I use it in tractor/trailer design?"*



Conclusions and Path Forward

- Code V&V and UQ is very important (even if code applications are focused solely on design)
- Need smaller y+ values at surface to obtain accurate solutions
- May need unsteady RANS or DES to accurately predict base flow (currently not funded at SNL)
- Continue 3D GTS solutions for turbulence model study:
  - k-omega
  - k-epsilon
  - Spalart Allmaras
- Continue 3D GCM Solutions (free)
- Document, document, document!
  - 10 degree yaw solution (free)
  - 2D GTS
  - 3D GTS (FY02 Grids)
  - 2D GCM (free)

Overview of LLNL Incompressible Flow Modeling and Development

Dora Yen Nakafuji, Jason Ortega,
Tim Dunn, Kambiz Salari, Rose McCallen

Lawrence Livermore National Laboratory

Heavy Vehicle Aerodynamic Drag Working Group Meeting
April 3-4, 2002

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

LLNL Project Goals

Focus

- **To provide industry with guidance on advanced computational methods and industry tools**
- **To identify and develop simulation techniques that can accurately predict the flowfield of heavy vehicles**
- **To investigate drag reduction strategies**

Approach

- **Investigate advanced simulation techniques using in-house tools that provide flexibility and access to internal resources**
- **Investigate flow structure associated with heavy vehicle aerodynamics such as gap flow and the wake**
- **Investigate feasibility of other available codes to aid industry**

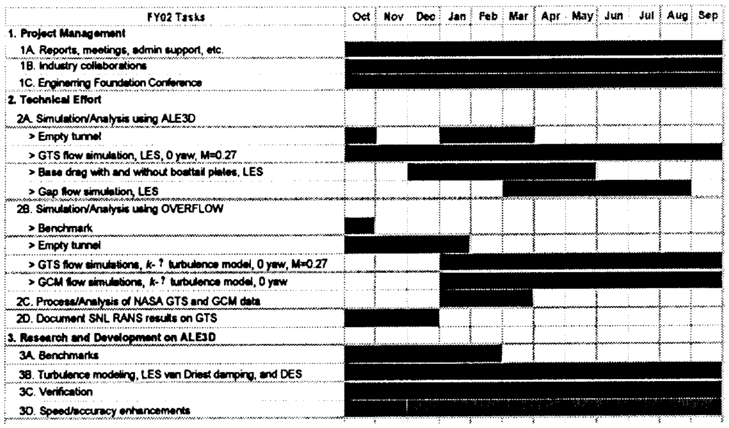
LLNL Budget for FY02

- FY02 $440 K
  - Project management
  - Engineering Foundation Conference
- Leveraging
  - ASCI code development program
    - Incompressible flow model development
  - ASCI White massively parallel computer
  - DoD/DOE Technology development program
    - Multiphase flow model development
  - LLNL Internal Tech Base Funding
    - Particle flow model development
  - NASA Ames collaboration
- Team Members
  - Dora Yen Nakafuji, Jason Ortega, Tim Dunn, Kambiz Salari, Rose McCallen

LLNL FY02 Tasks

- **Code speed up**
  - *Implicit/Semi-Implicit* Projection methods
- **Gap flow simulation**
  - Stable flow structure with/without side extenders, low drag
  - Unsteady flow structure, high drag
  - Experimental data from USC and NASA
- **Trailer wake simulation**
  - Analysis of flow structure with/without boattail
  - Wake/Ground-plane interaction
  - Experimental data from NASA
- **Full vehicle simulation with OVERFLOW**
  - Tunnel simulation to determine proper outflow BC
  - GCM flow simulation in the NASA 7'x10' tunnel

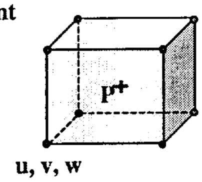
LLNL Anticipated Deliverables for FY02



Solving 3-D Unsteady Incompressible Navier-Stokes Equations, ALE3D

Galerkin Finite-Element Method, Q1Q0 Element

- **8-node Hexahedral Brick Elements**
- **Tri-linear Velocity**
- **Piecewise Constant Pressure**
- **Explicit formulation**



Implemented Implicit/Semi-Implicit projection methods to remove stability constraint on time step due to Courant and viscous restriction

Incompressible Flow Code Development

Implicit Projection Method (Tim Dunn)

Step 1: Approximate a pressure field
Initialize pressure from the previous time-step

$\widetilde{P} = P^n$

Step 2: Solve momentum equations for the intermediate velocity field

$$\left[M + \Delta t\left(K + N(u^*)\right)\right]\widetilde{u} = Mu^n + \Delta t\left[F - MM_L^{-1}C\widetilde{P}\right]$$

Step 3: Project to a divergent-free field

$$\left[C^T M_L^{-1} C\right]\lambda = C^T \widetilde{u} \qquad u^{n+1} = u^n - M_L^{-1} C\lambda$$

Step 4: Update pressure

$$p^{n+1} = p^n + \lambda/_{\Delta t}$$

Timing the Projection Method

Two-dimensional wake simulation

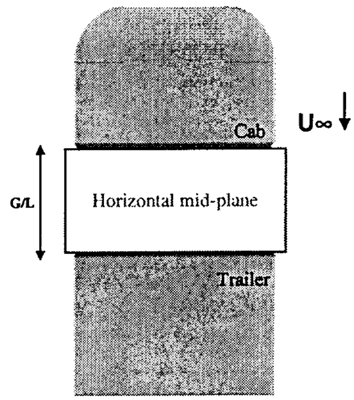
- **20,000 elements**
- **16 processor on IBM SP2 machine**

	Explicit	Semi-Implicit
Time Step *(s)*	3.9e-8	1.7e-5
run time/cycle *(s)*	3.24	4.77
1 second of simulation time	961.5 days	3.2 days

Semi-Implicit is about 300 times faster than explicit

USC Experiment, Gap Flow Investigation

PIV measurements in horizontal mid-plane



$$Re = \frac{U\sqrt{A}}{\nu} = 300{,}000$$

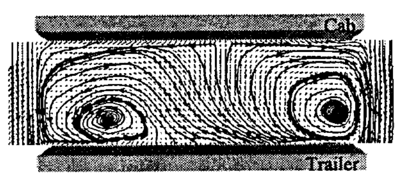
A - Frontal area

$$\frac{G}{L} = \frac{G}{\sqrt{A}}$$

USC Experiment, Small Gap

Time-averaged streamline patterns

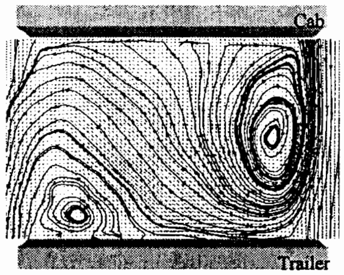
G/L = 28%



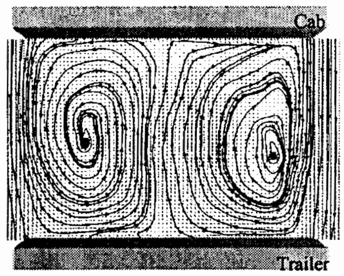
Symmetric flow

USC Experiment, Large Gap

Time-averaged streamline patterns, G/L = 75%



Asymmetric flow



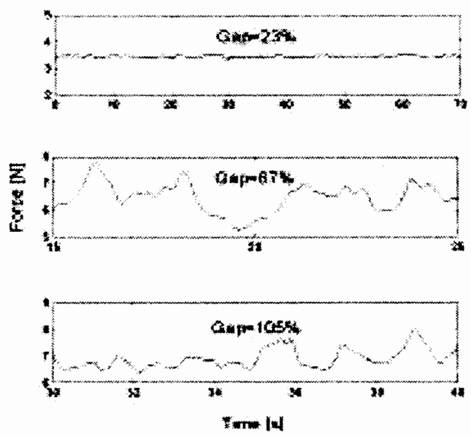
Symmetric flow

Gap flow structure is sensitive to the condition of the shear layer
Large side force may be present in the asymmetric flow case

USC Experiment, Time History of Drag Force

Time signature of drag force on trailer as a function of gap size

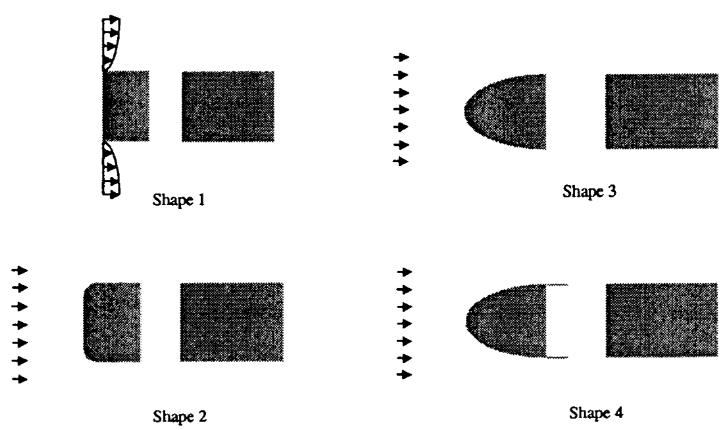
Re = 305,000



Gap Flow Simulation, Computational Approach

- Gap flow from experimental observation is clearly three-dimensional
- Perform 2-D simulations to determine proper length and time scales needed to resolve flow structures in the gap
- Given the knowledge of the 2-D calculations perform 3-D simulations
- The computational domain is setup to capture the gap and part/all of the tractor and part of the trailer geometry

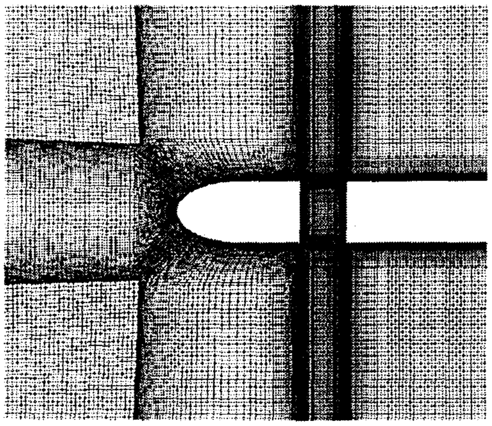
Computational Domain and Geometry



Computational Mesh for G/L at 72%

Unstructured Mesh

40,000 elements

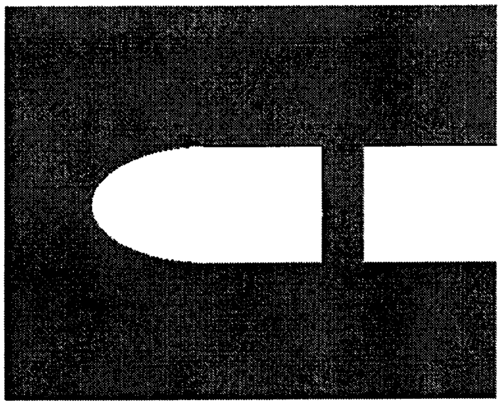


Gap Flow Simulation Matrix

G/L	Smagorinsky	Smagorinsky with Van Driest Damping
35%	Completed	Completed
72%	Completed	Completed
72% with side extenders	Completed	Completed

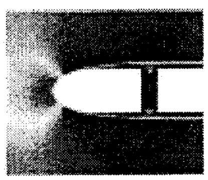
Gap Flow Simulation, G/L of 35%

Smagorinsky

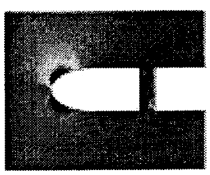


Gap Flow Simulation, G/L of 35%

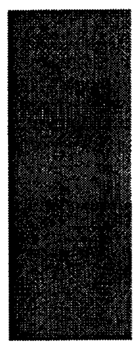
Time-averaged results, Smagorinsky



U-comp.

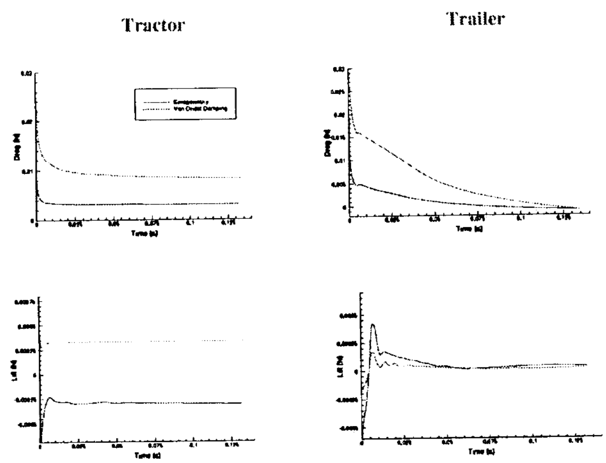


V-comp.



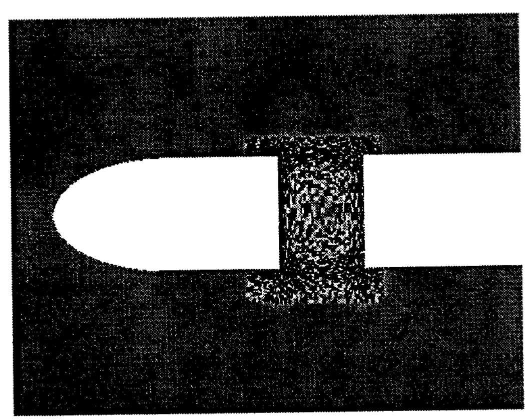
Pressure

Time History of Drag and Lift, G/L of 35%



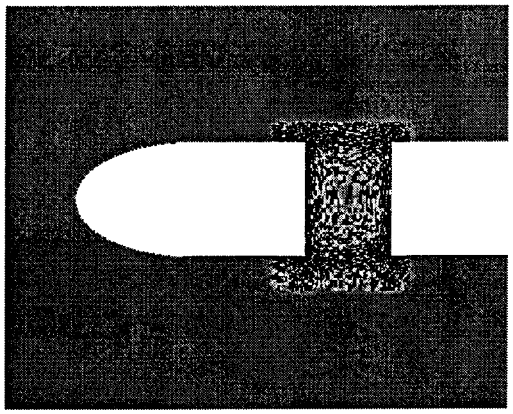
Gap Flow Simulation, G/L of 72%

Smagorinsky



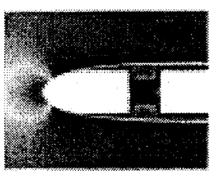
Gap Flow Simulation, G/L of 72%

Smagorinsky with van Driest damping

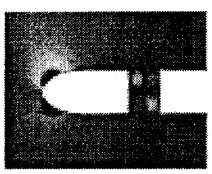


Gap Flow Simulation, G/L at 72%

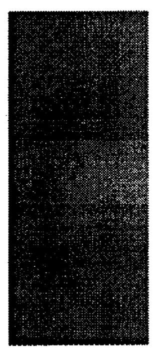
Time-averaged results, Smagorinsky



U-comp.



V-comp.

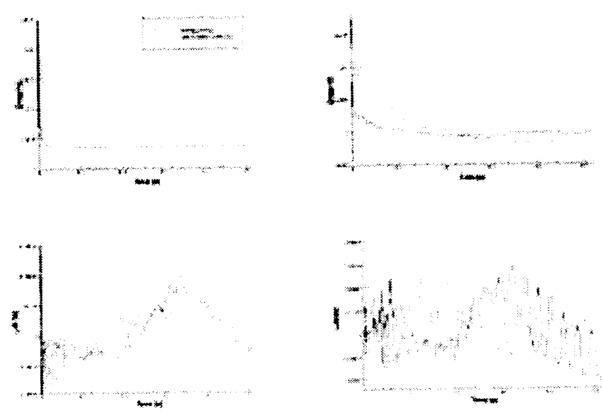


Pressure

Time History of Drag and Lift, G/L of 72%

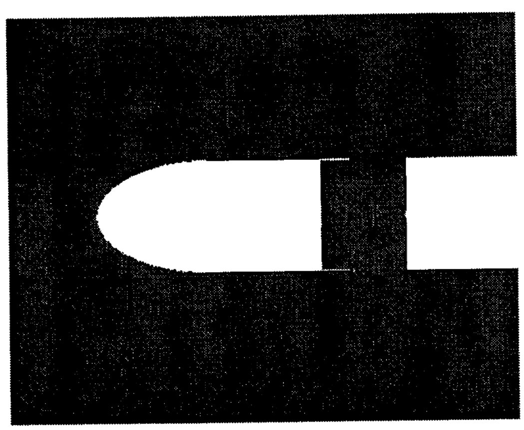
Tractor

Trailer



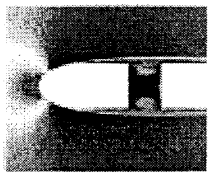
Gap Flow Simulation, G/L at 72% with Side Extenders

Smagorinsky

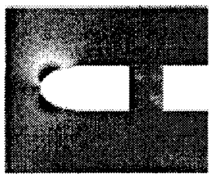


Gap Flow Simulation, G/L at 72% with Side Extenders

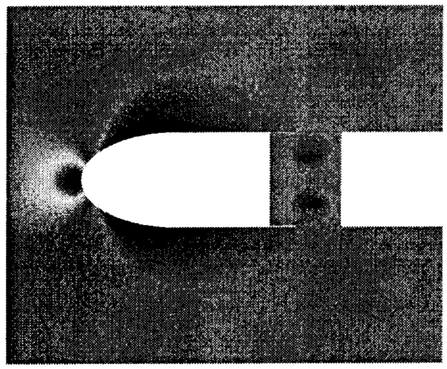
Time-averaged results, Smagorinsky



U-comp.



V-comp.

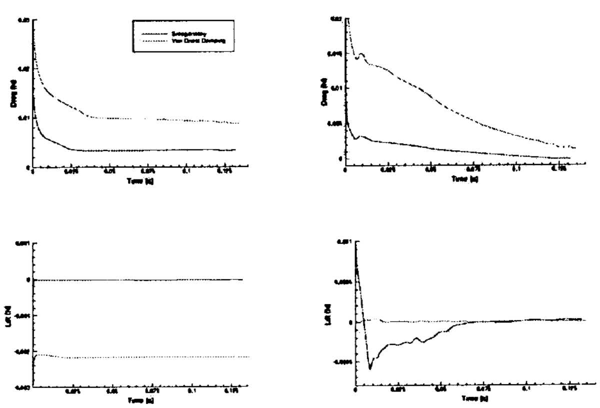


Pressure

Time History of Drag and Lift, G/L of 72% with Side Extenders

Tractor

Trailer



Summary

- Implicit and Semi-Implicit projection methods have been implemented in ALE3D. Anticipate significant speedup with all simulations
- Initiated gap flow study with gap distances below and above the critical distance, G/L of 50%. Also, investigated the impact of side extenders on gap flow structure
- Initiated Trailer wake flow simulation with/without boattail to investigate the wake structure and its interaction with ground plane
- OVERFLOW was utilized with its overset grid capability to model NASA 7'x10' tunnel for boundary condition determination
- An overset mesh which is a modular mesh is under construction for the tractor-trailer geometry in the NASA 7'x10' tunnel

Validation Cases and Truck Wake Simulations with ALE3D

Jason Ortega, Tim Dunn, Dora Nakafuji
Rose McCallen, Kambiz Salari

Lawrence Livermore National Laboratory

Computational Physics
Fluid Dynamic Applications

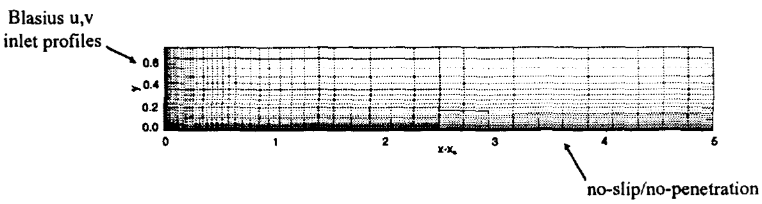
Overview

- Validation Test Cases with ALE3D
  - Flat Plate
  - Circular Cylinder
- 2-D Truck Wake Simulations
- Summary

Validation Cases with ALE3D

Validation Case Flat Plate

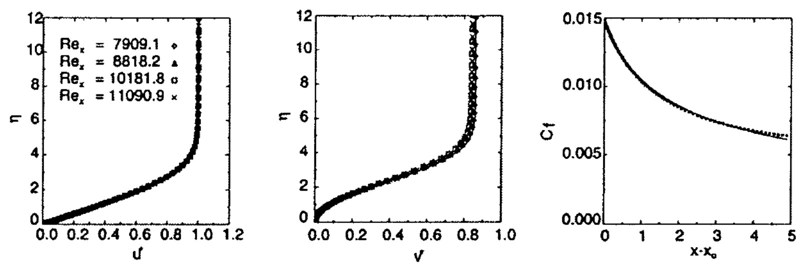
Testing ***viscous growth*** of a boundary layer and ***shear stress prediction***



- $Re_{x\ inlet} = 2{,}000$
- ***Explicit*** and ***implicit*** time-integration schemes
- Coarse grid: 2,440 elements
- Medium grid: 9,760 elements

Validation Case   Flat Plate

Horizontal Velocity   Vertical Velocity   Shear Stress Coefficient

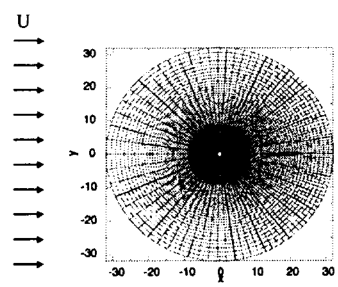


Good representation of ***laminar boundary layer development*** with ALE3D

Validation Case   Circular Cylinder

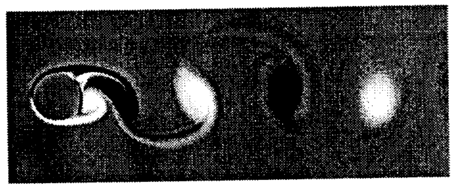
Testing ***unsteady vortex shedding*** and ***drag prediction***

uniform inlet velocity profile



- Re_d= 1,000
- ***Explicit*** time-integration scheme
- Coarse grid: 20,000 elements
- Medium grid: 80,000 elements

Validation Case Circular Cylinder



Measured Quantities

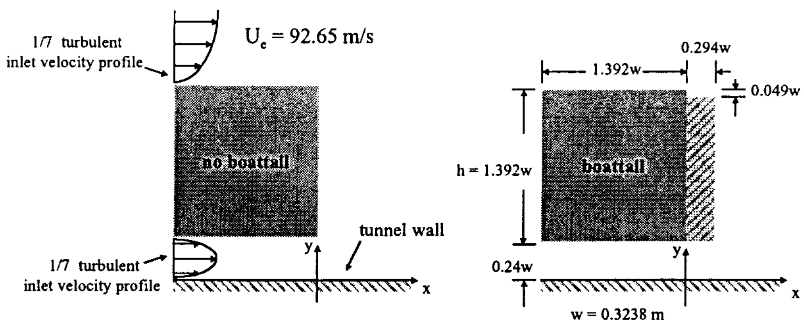
Grid	C_d	C_l	$St = fD/U$
Coarse	1.4429	-0.001044	0.2288
Medium	***1.5021***	-0.000026	***0.2394***
Qian & Vezza	1.52	–	0.24
Blackburn *et al.*	1.51	–	–
Behr *et al.*	1.53	–	0.241
He *et al.*	1.5191	–	–

Capturing ***drag forces*** and ***laminar vortex shedding*** with ALE3D

2-D Truck Wake Simulations

Computational Setup

Investigating ***length scales***, ***vortex dynamics***, influence of the ***ground plane***, and the ***effect of add-on devices***

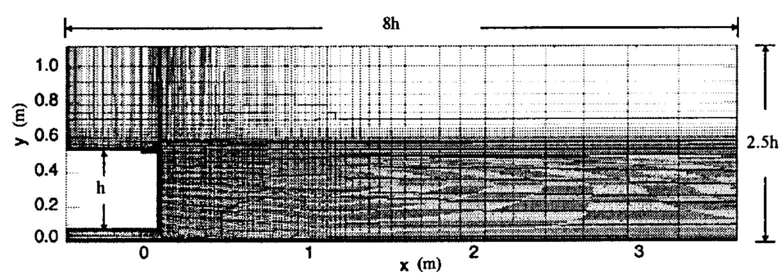


- 2-D simulation with ALE3D
- LES with Van Driest damping
- $Re_w = 2 \times 10^6$

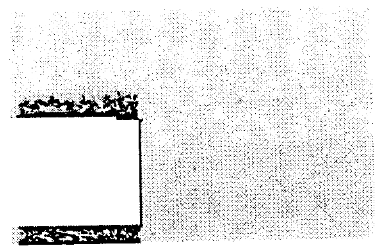
Computational Grid

Boattail

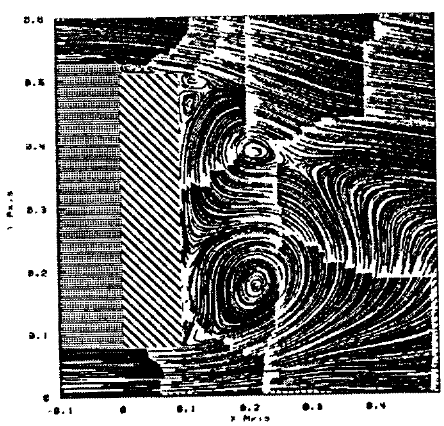
19,445 elements



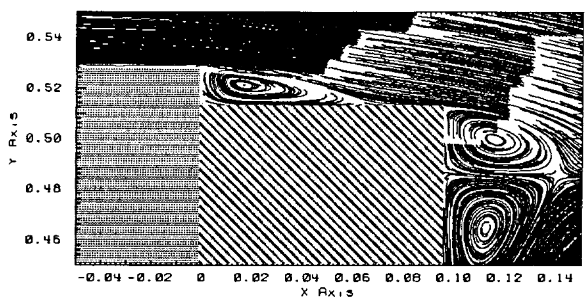
Vorticity Measurements



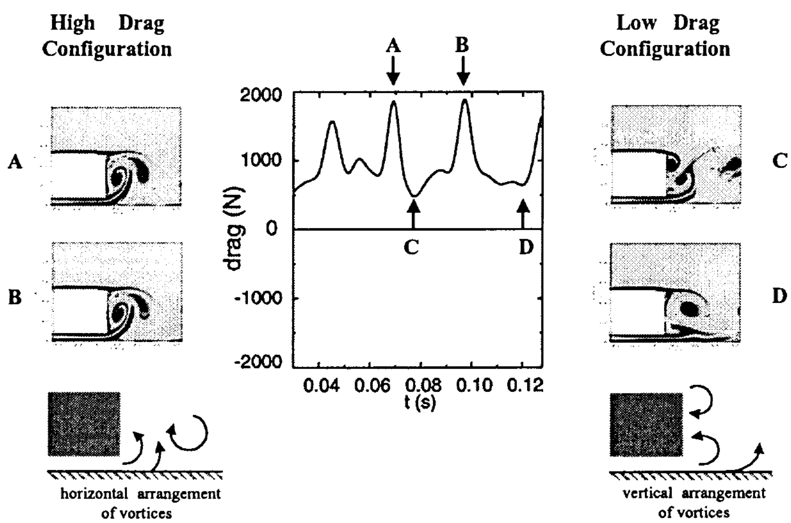
Average Streamline Fields



Average Streamline Fields



Drag Measurements



Summary

- Validation Cases with ALE3D
  - ***Velocity profiles*** and ***shear stress coefficient*** from the flat plate simulation compare favorably with those from the ***Blasius solution***
  - ***Drag coefficient*** and ***shedding frequency*** from the circular cylinder simulation show good agreement with results in the ***literature***
- 2-D Truck Wake Simulations
  - Capture the ***unsteady nature*** of ***vortex shedding*** in the wake
  - ***Drag*** is ***strongly influenced*** by the ***arrangement of the vortex patches*** in the near wake
  - Set the ***groundwork*** for future 3-D simulations by determining the ***length scales*** and ***required resolution*** of the flow field

Full Vehicle Simulation Using OVERFLOW & Overset Tools

Dora Nakafuji, Jason Ortega, Tim Dunn,
Rose McCallen, Kambiz Salari

Lawrence Livermore
National Laboratory

The Bridge

ALE3D/SACCARA
Turbulence Models
CFD code development

CONTINUING RESEARCH & DEVELOPMENT

Configuration studies
Overflow/Overset Tools

APPLIED R&D

Industry codes
Production expertise
Processes/methods

INDUSTRY APPLICATION & PRODUCTION DESIGN

Motivation

- Robust and well tested RaNS code
- Provide a secondary tool for evaluating flow models and experimental results
- Incorporate Overset techniques & capabilities in simulation
- Build in modular & interchangeability into grid development process

Break-up complex geometries	+	Independence in generating grids	=	Simplification & Increased Capability

Objectives

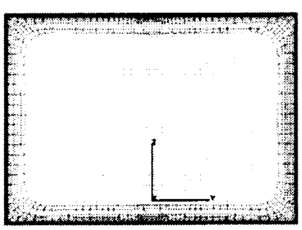
- Integrate benefits of Overflow & Overset grids
  - —RaNS speed and near wall modeling capabilities
  - —Gain experience using empty tunnel configuration
  - —Apply tools to GCM simplified model
- Use Overset modular capability to analyze multiple truck configurations (gap, side angle) and complex geometries
- Address industry analysis needs by quantifying simplification on grid generation and establish methodologies for modular analysis

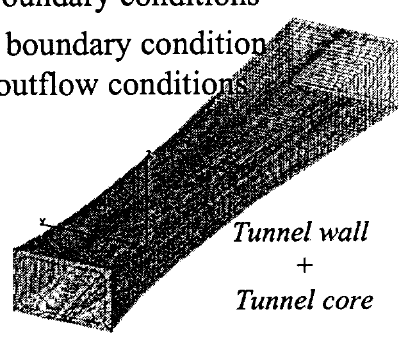
Accomplishments

- 3-D empty tunnel simulations
  - —Viscous boundary conditions along all walls
  - —Overset grid (approx. 1 million pts)
- Strengthened ties with collaborators
  - —Leveraged grid generation resources (NASA Ames, LLNL Overture Group)
  - —Fast-tracking knowledge transfer of Chimera techniques
- Develop Overset grids GCM truck
  - —Used tried&true grids (collars, caps)
  - —Integrated interchangeability into grid design
  - —Potentially refined & reduced grid complexity (approx. 4 million pts)

Empty Tunnel Grid

- 3-D Overset grid — O-core with rectangular wrap on tunnel wall
- Simplified and reduce boundary conditions
- Consistent viscous wall boundary conditions and appropriate inflow/outflow conditions

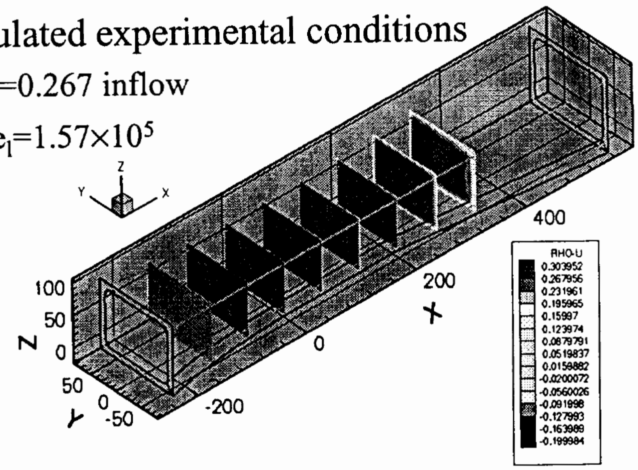




Tunnel wall
+
Tunnel core

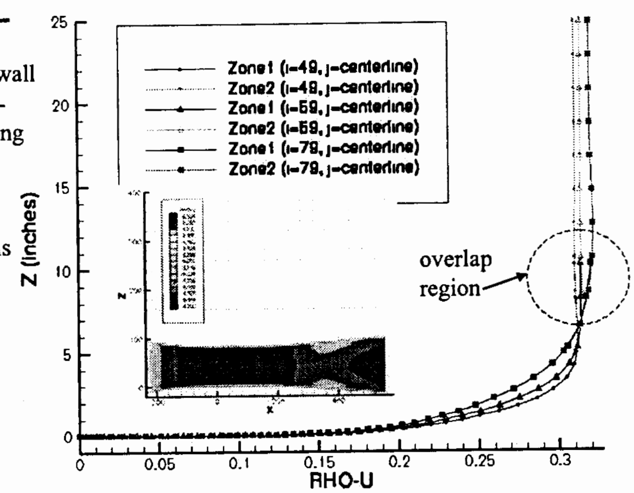
Empty Tunnel Simulation

- Simulated experimental conditions
  - —M=0.267 inflow
  - —$Re_l = 1.57 \times 10^5$



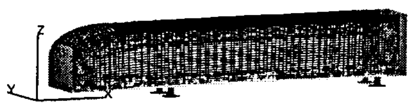
Simulation Results

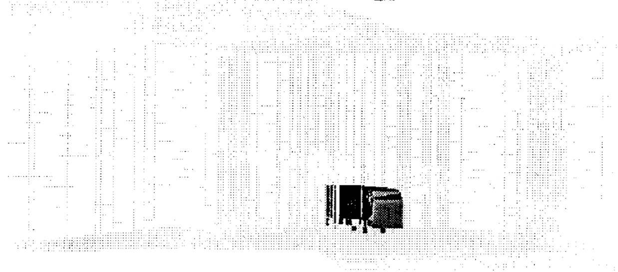
- Profiles at the wall in the tunnel test-section taken along the y-centerline
- Zones indicate multiple grids
- Overlap regions are consistent



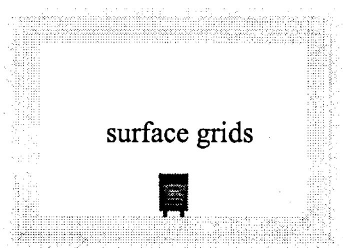
GCM Truck Grids

- Pre-liminary grids for truck (approx 4 mil pts)
- 8 multi-grids, optimized spacing and clustering to surface
- Minimal tunnel changes to accommodate truck

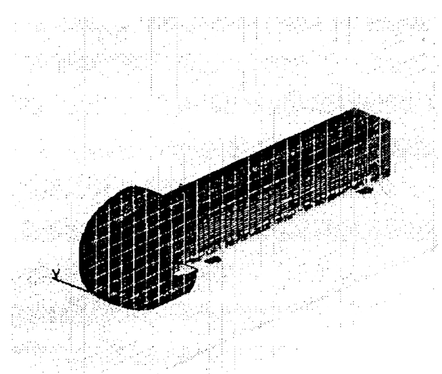




Truck with Tunnel Grids

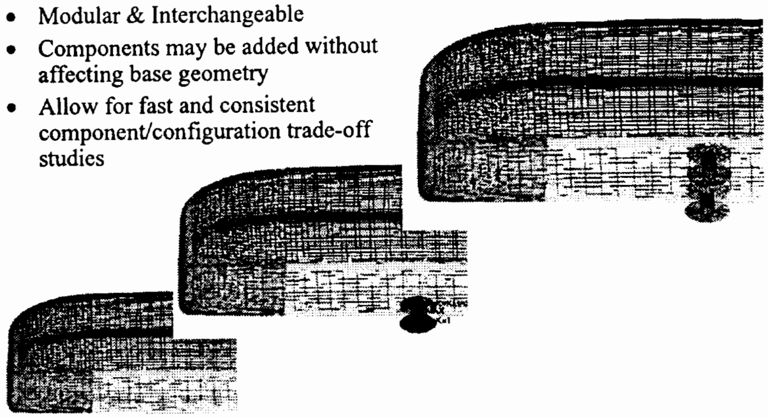


Generation of front cap volume grid



Grid Interchangeability

- Modular & Interchangeable
- Components may be added without affecting base geometry
- Allow for fast and consistent component/configuration trade-off studies



Caltech Heavy Vehicle Aerodynamics Computational Group

Prof. Tony Leonard

Demosthenes Kivotides, Postdoctoral Scholar

Mike Rubel, Graduate Student

Philippe Chatelain, Graduate Student

Graduate Aeronautical Laboratories · California Institute of Technology

April 3-4 2002

Vortex Code: Essentials

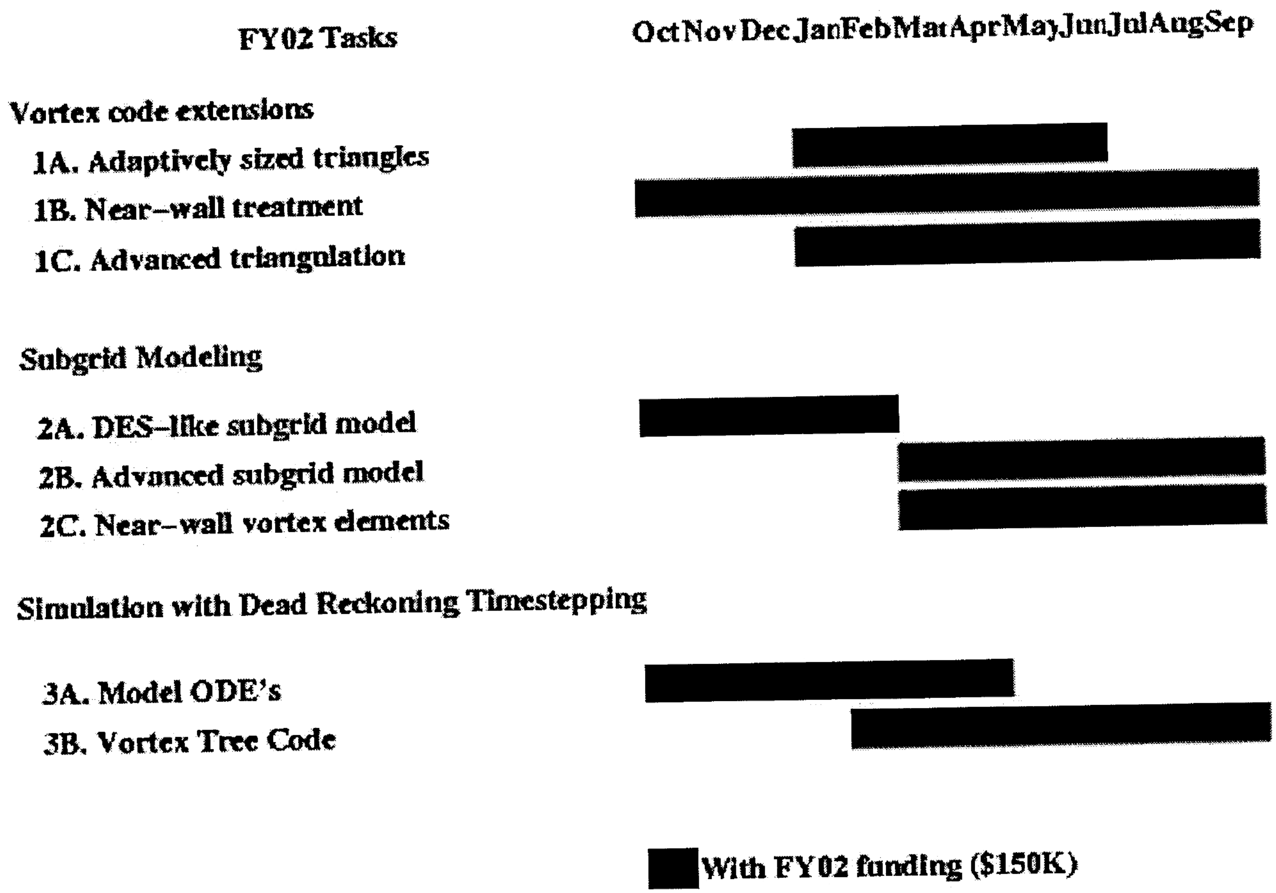
- Numerical technique to solve the Navier-Stokes equations
- Suitable for Direct Simulation and Large-Eddy Simulation
- Uses vorticity ($\vec{\omega} = \nabla \times \vec{u}$) as the solution variable
- *Lagrangian*: computational elements move with fluid velocity
- Viscous, 3-D, incompressible, with boundaries

Vortex Code: Advantages

- Computational elements only where vorticity is nonzero
- No grid in the flow field
- Only 2-D grid on the vehicle surface
- Boundary conditions in the far field automatically satisfied

now: examples of vortex particle codes in action

Caltech FY02 Planned Work



Current Research Topics Topics

- Boundary geometry (GTS model, USC geometry, others)
- Near-wall treatment
- Dead-Reckoning time integration algorithm
- Vortex filament methods
- SGS / LES models
- Face-centered cubic lattice

Geometry and Boundary-related Research

- Need to know information such as closest-point, closest-panel, inside/outside
- Traditionally limited to simple shapes like spheres and cubes
- GTS geometry requires more robust approach
- Implementing half-edge data structure
- Possibly novel tree-based algorithms for the above

Near-Wall Treatment

- Particles good approximation for field in free-space, but not near wall
- Near-wall Eulerian treatment, local grid, ”thick” boundary
- Match to particles, LES further afield
- Some low-D progress; trying to expand

The Dead Reckoning Algorithm

$$\frac{dX}{dt} = F(X, t) \qquad X(t_0) = X_0$$

- Conventional time integrator integrates every variable, every timestep
- Implemented new algorithm that automatically adjusts step size
- Closely related to dead reckoning network games algorithm
- See mass-spring animations
- How to make it work with our fast multipole tree?

Vortex Filament Method

- Instead of particles, discretize vorticity on set of filaments
- Automatically divergence-free
- Efficient in free-space
- Boundary compatiblity work in progress
- Use to model flow in wake?

Additional topics

- LES models for vortex methods
- FCC lattice for remeshing

Commercial CFD Code Validation for Heavy-Vehicle Aerodynamics Simulations

David Pointer, Tanju Sofu, David Weber - Argonne National Laboratory
Everett Chu, Paul Hancock, Bob Bundy - PACCAR Technical Center

Heavy Vehicle Aerodynamic Drag Team Meeting
LLNL, April 3-4, 2002

Background

- Next generation of computational methods/tools are currently being developed under the DOE's Heavy Vehicle Aerodynamic Drag Program
  - focus on specific turbulence and flow separation problems unique to heavy vehicle external aerodynamics
  - a wide range of turbulence modeling options
  - experimental program to support V&V efforts
- Specific elements of the program
  - long term focus
  - need for massively parallel high-performance computers
  - need for extensive verification and validation based on simple geometries

Objectives of ANL Effort

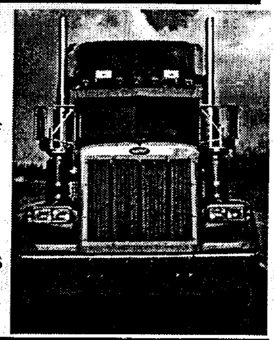
- Assessment of commercial CFD capabilities for heavy-vehicle aerodynamics
  - extend general purpose turbulence models to aerodynamics applications
  - investigate standard turbulence models and some of the novel turbulence modeling capabilities
- Specific elements of the activity
  - near term focus (address immediate needs of manufacturers)
  - reduced reliance on high-performance computers (compatible with OEMs' computational resources)
  - realistic heavy vehicle geometries (full details of a specific design)
- Initial contacts with manufacturers indicate support and interest
  - CRADA application with Paccar Technical Center, and interactions with Freightliner
  - Strong CFD industry support (particularly from CD/adapco and EXA)

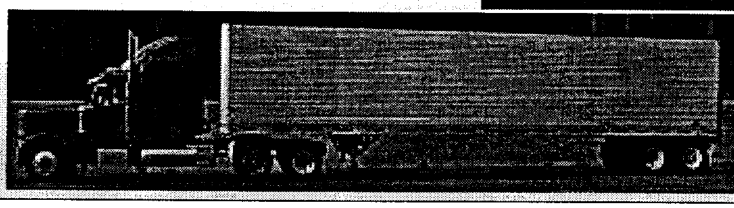
Commercial CFD Software

- Common advantages
  - ability to model complex geometries with selective mesh refinement (unstructured grids)
  - extensive V&V work by developers and user community for a wide range of CFD applications
  - reduced need for large scale computer systems
  - development and technical support from the vendor
- Common issues
  - insufficient accuracy, high cost
  - need for CFD specialists familiar with specific software
  - need for assessment of codes' strengths/weaknesses
    - standard turbulence models generally validated for automobile industry, but assessment needed for heavy-vehicles
    - validation and assessment needed for novel turbulence models

ANL - PACCAR CRADA

- Detailed geometry for identified vehicle configurations (Peterbilt-379 selected as the base model)
- 1/5-scale wind tunnel tests in University of Washington with selected configurations
- Assessment of STAR-CD (and possibly PowerFlow) software
- 18 month, $600K plan (equal contributions by each partner)





ANL - PACCAR CRADA (cont.)

- Phase-I work
  - Build 1/5-scale model of the base configuration and conduct wind tunnel tests
  - Collect, organize, and process the experimental data
  - Assess standard RANS model of STAR-CD (high Reynolds number form of _-_ equations in conjunction with the "law of the wall" representation of flow)
  - Blind predictions of the flow field to avoid "tuned" solutions
- Phase-II work
  - Fine-tuning of STAR-CD model
  - Assessment of more detailed turbulence modeling options to address the limitations of the standard RANS model
  - Analysis of additional heavy-vehicle configurations (new designs)
- Possible extension of work for assessment of PowerFlow

Summary

- Provide an independent and comprehensive evaluation of commercial CFD capabilities to address near-term goals of the Heavy-Vehicle AeroDrag Program
  - realistic and prototypic 3-D geometries and operating conditions
  - close collaboration with PACCAR to address their current needs
  - CFD industry support
- Deliver a summary of best practice guidelines for application of current commercial CFD capability to heavy vehicle industry.

21st Century Truck Partnership
"Unprecedented Collaboration for Unparalleled Results"

Aerodynamic Combination Vehicle Test Update/DOE

Georgia Tech Research Institute
Great Dane Trailers
Volvo Trucks North America

/Skip Yeakel, P.E.

Aerodynamic "SWAT Team" Meeting
@ Lawrence Livermore National Lab, Livermore, CA
April 4, 2002

Aerodynamic Combination Vehicle Team Members

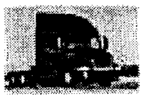
21st Century Truck Partnership

- Georgia Tech Research Institute
  Atlanta, GA
- Great Dane Trailers
  Savannah, GA
- Novatek
  Atlanta, GA
- Volvo Technology of America
  Greensboro, NC
- Volvo Trucks North America
  Greensboro, NC

"Tuning" Test Process & Prospects - Greensboro, NC

21st Century Truck Partnership

- **Abbreviated road course**
  - 65 mph speed limited section (~ 5.5 mi.) of U.S. Route 311 south of I-40
  - Quick cycle time - 7 test variables/14 runs completed on March 1st, 2002
  - Constant speed runs/adaptive cruise control operation--north and south
  - Minimal traffic = no runs lost (100% yield)/ March 1 (public highway)
- **Prospects**
  - "Flavor" for TRC testing but results not statistically significant
  - Volvo VN Integral Sleeper™ ("660" model - seats driver + 3 observers) -|
  - "Quick turns" = more exciting than watching paint dry (e.g. TRC) V
  - Economical = federal highway road course (a/k/a "free")
  - Better weather prospects vs. Ohio



- **Limitations**
  - Not flat (rolling hills)--hard to integrate spikes, some traffic, speed limited (65 mph), too short for statistically significant results (un-"scientific")
  - Experimentally "impure"...baseline was NOT "stock" trailer; too painful!

TRC Hopes (and Expectations)

21st Century Truck Partnership

- **Akin to watching paint dry--if all goes well...a plethora of angry trucker language likely if not!**
  - No place for a cast of thousands, 800, or even...eight!
  - Watching wind blow or rain fall is neither fun nor productive.
  - ~ 450 miles per data point--requires man/machine harmony and incredible patience possessed by few.
  - Once cruise control is set, the driver has only one task...to stay within the assigned lane
- **55, 65, and 75W (or 60, 70E, and 80?--concerns!) mph test runs**
- **Results that are even half as good as predictions...no apologies needed if xx% net fuel savings can be proven!! CAUTION urged re NC "tuning" data...usefulness is software limited and should only be construed as serving the tuning purpose intended. The TRC site and "high tech" (NOT!) buckets of fuel and stopwatches are still the best (ONLY!) way to get precious, tedious, datapoints.**
- **Don't try this work at home--very few such sites around the globe!**

Aerodynamic SWAT Team CFD Wish List

21st Century Truck Partnership

- Reduce cost of current CFD tools for industry/society benefit.
- Aerodynamics lasts for the life of a truck--for better or worse! Seek out optimal, and practical, design concepts with industry.
- Advance the art of the aerodynamicist--more near term blood in that turnip than in environmentally squeezed IC engines.
- Provide economical tool to judge add-on devices--a better way to separate good product concepts from snake oil.
- Maintain/expand aerodynamic R&D community and relationships; east (e.g. Langley FST, PSU+) and west (current+)...even global?!
- Correlate/coordinate with industry partners and established methodologies (road AND wind tunnel tests).
- Partner with/support other agencies for common cause via cohesive NEP (e.g. EPA/DOT "Ground Freight," DOD "Army Transformation," et al) under 21st Century Truck Partnership umbrella with all (16) industry partners (incl. ALL truck OEMs).

Undesirable Aero SWAT Team Product

21st Century Truck Partnership

Solicit "voice of the customer"--don't create in a vacuum!

Undesirable Aero SWAT Team Goal

21st Century Truck Partnership

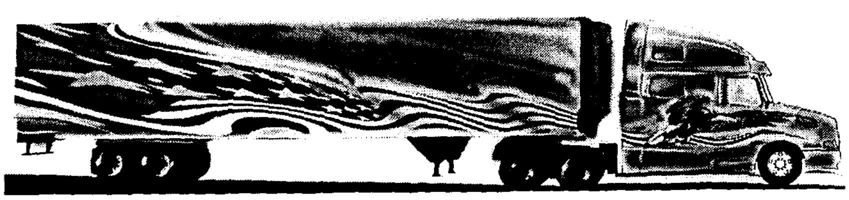
Common truck design by committee--no matter how fuel efficient!

Aerodynamic Prospects and Importance

21st Century Truck Partnership

Aerodynamics or more wasted OFFSHORE oil? It's an American choice to make.

Combining forces will help us get it together. We have made a good start...the best is yet to come!



21st Century Truck Partnership
"Unprecedented Collaboration for Unparalleled Results"

Thanks, and be thankful for the opportunities before us!

--Questions and Answers--

VOLVO

New Roads.

Aero "SWAT Team" Meeting @ LLNL, Livermore, CA
April 4, 2002